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RESEARCH AND DEVELOPMENT OF MATERIEL

ENGINEERING DESIGN HANDBOOK

# ELEMENTS OF ARMAMENT ENGINEERING PART THREE WEAPON SYSTEMS AND COMPONENTS

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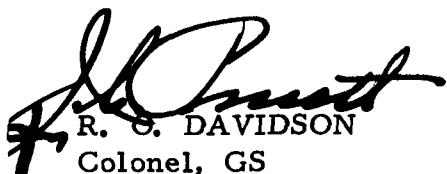
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ELEMENTS OF ARMAMENT ENGINEERING

PART 3, WEAPON SYSTEMS AND COMPONENTS

LIST OF ILLUSTRATIONS

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PREFACE

History will reveal that the greatest advances in science have occurred during periods of major world conflicts. In this regard, World War II was no different from the wars which preceded it. Consider a few of the major technological advances that were made between 1940 and 1945; the creating and harnessing of nuclear energy; the introduction of thermal jet propulsion; the development of ground, shipboard, and airborne radar systems and of complex computing equipment; and the development of rockets and rocket-propelled short and intermediate range guided and unguided missiles. Unlike past examples in history, however, the engineering effort associated with this war did not stop with the end of hostilities. The continuation of the cold war has kept the urgency of discovery and the requirement to maintain technical leadership alive. The fact remains that we are right now in the throes of the greatest major engineering effort that the world has ever known. The engineering effort of today differs in two ways from the customary engineering practices found prior to World War II: in the very large size of the projects, and in the tremendous scope of the undertakings. It is in the second of these areas that the systems engineering concept might be said to have been born.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont)

TABLE OF CONTENTS (cont)

TABLE OF CONTENTS (cont)

TABLE OF CONTENTS (cont)

TABLE OF CONTENTS (cont)

TABLE OF CONTENTS (cont)

Chapter 11 (cont)

CHAPTER 12

FUZES

TABLE OF CONTENTS (cont)

CHAPTER 1

INTRODUCTION TO SYSTEMS ENGINEERING

1-1 INTRODUCTION

Systems engineering, or, of more particular application to the military, weapons systems engineering, means the successful creation, with the minimum expenditure of time, of a complete system in which the interrelationship of all components of the system and of all conditions which might influence the system are considered in proper perspective. (In its simplest terms systems design is the design of an integrated system rather than putting together a collection of independently designed components.) The problems generated by each new design are in themselves put into proper perspective and solved in terms of their ultimate effect on the program. This is but the application of common sense to the problem of overall design. The practical and obvious solutions are not always the simplest and easiest to achieve. This point can be shown by referring to the manufacture of the relatively uncomplicated bombers of World War II. In these programs it was not uncommon to find that an airframe which had been manufactured to meet all requirements imposed on it by the Army Air Force, could not accommodate the navigational and bombing equipment designed by another company. In both cases the requirement of manufacture of the individual items had

been met by both manufacturers. However, in the marrying of the components, the end product was not always acceptable. The systems engineering concept minimizes the possibility of the occurrence of such undesirable situations.

This example illustrates the requirement of manufacture of round pegs for round holes. The weapons of the armed forces, however, must, as systems become even more complicated and sophisticated, take on a much more complex pattern. In the development of new weapons, it becomes impossible for one individual or even a single organization to specialize in all the engineering areas required for the development of an integrated weapon system; hence, groups of scientists and engineers must work together as a team, combining all knowledge and experience in the fields of aerodynamics, ballistics, propulsion, guidance and control, and electronics, in an effort to develop a single weapon. The weapon system developed by the techniques of systems engineering, must be integrated with testing and check out equipment, with ground launching, handling and guidance equipment, and fitted to the needs of its human operator and its environment.

1-2 WEAPONS SYSTEMS REQUIREMENTS

To initiate the development of a new weapon system, the military services first develop statements of military requirements. These statements indicate the specific need for the new weapon system on the basis of the anticipated military situation and enemy capabilities at the time that it is anticipated the system will be active. They attempt to anticipate technological advancements that might be expected during the development period. The military requirements also state the use to which the system is to be put and define the desired military characteristics.

The thought that must go into the preparation

of a set of military requirements is comprehensive. The requirement must be based on, but is by no means limited to, a careful analysis of known and estimated enemy capabilities; the analysis of conclusions obtained from actual combat and combat exercises; the present inventory of in-service weapons and their capabilities; the proposed characteristics of sister weapons under development; recommendations of field commanders; and the detailed evaluation of the technical progress and potential of industry. These are but a few of the many factors considered in formulating the military requirement.

1-3 MILITARY CHARACTERISTICS

The remainder of this chapter will be focused on the selection of missile characteristics to meet the specific requirements of a system. A missile system's general characteristics might include:

1-3.1 AIRFRAME

(a) Range, speed and maneuverability.

(b) Ballistic or aerodynamic type trajectories (or a combination of each).

(c) Length and diameter requirements.

(d) Weight requirements.

(e) Consideration of aerodynamic stability, aerodynamic control, launch peculiarities, aerodynamic heating, flutter, aerodynamic loads, fluid flow, etc.

1-3.2 PROPULSION SYSTEM

(a) Selection of propulsion unit.

(b) Range, speed, and altitude operating conditions.

(c) Fuel characteristics, I_{sp}, etc.

(d) Materiel requirements.

(e) Thrust requirements.

1-3.3 GUIDANCE SYSTEM

(a) Selection of basic system.

(b) Accuracy requirements.

(c) Weight and dimensional limitations.

(d) Characteristics of individual components.

1-3.4 WARHEAD

(a) Size and weight.

(b) Desired effect.

(c) Yield.

(d) Altitude limits between which weapon is to be effective.

1-3.5 RELIABILITY

(a) Reliability of each component of the main system. In this area it must be remembered that the overall reliability of the system is the product of the reliability of the individual components making up the system.

(b) Performance of servicing crews.

(c) Reliability of the ground handling system.

(d) Availability of logistical support.

(e) Hit probability.

(f) Reliability of fuzing system, and several other factors which characterize the particular system.

The following sample military requirements are typical of some which might be used to initiate work on a particular weapons system. From these requirements specific military characteristics would be prepared for each system.

1-3.6 SAMPLE MILITARY REQUIREMENTS

(a) To develop a system that is capable of 85 percent probability of kill of low flying aircraft (1000 yd to 17,280 yd range) at aircraft speeds up to Mach 2 and at altitudes of from fifty feet to thirty thousand feet.

(b) To develop a system capable of delivery of a warhead having a blast effectiveness against a six foot reinforced concrete emplacement at ranges of from six hundred to fifteen thousand yards and having a CEP of ten yards.

(c) To develop a strategic system that is capable of allowing the delivery of a nuclear warhead of no less than 1-MT to a range of 5000 nautical miles and with a CEP of no more than a mile. The system to be operational within four years from the date of negotiation of the contract.

(d) To develop a system that will be capable of allowing reconnaissance of an aggressor nation's homeland. The system to be observer-manned and possess a radius of operation of twelve thousand miles. Total time of flight to be no greater than four hours.

The final performance of the system will be measured in terms of probability of kill or probability of inflicting the required level of damage against a particular target. In terms of this evaluation, the factors which typify the performance of the selected system must be considered in great detail. (The reader may well review the discussion of overall kill probability and related factors which were presented in Chapter 6 [Part 2] of this text.)

1-4 SUMMARY

The major requirement today in the development of new weapons systems is to assure that the United States is the first to possess in operational status the latest types and largest numbers of offensive weapons. The ballistic missile race is a case in point. The successful completion of these projects requires an extremely well integrated program. The systems engineering concept provides a better system than has been used in past years to meet this requirement.

REFERENCES

Goode and Machol, *Control Systems Engineering,*
Mc-Graw-Hill Company, Inc., 1957.

CHAPTER 2

CONTROL SYSTEMS

2-1 INTRODUCTION

A control system controls a source of power. The input to the system is a command which causes the power to vary within the system, resulting in an output dependent upon the input. The output could be the position of a gun turret, the pitch attitude of a missile, or even the temperature of a room. The input is a small signal which must be amplified by the control system so as to influence the output.

An open loop control system (Figure 2-1) can be depicted as an amplifier and motor attempting to position a large, heavy wheel. One turn of the handcrank (input) should result in one turn of the wheel (output). But, after the wheel has rotated to its new position, there is no guarantee that the output will equal the input position. An open loop system cannot correct for natural imperfections in the linkages, gears, and motors. Such a control system is evidently too inaccurate for precision control requirements. The remainder of this chapter will discuss closed loop control systems which are capable of self-correction, and are, therefore, inherently accurate.

2-2 CLOSED LOOP SYSTEMS

An open ended system, as discussed above, can be improved by the addition of a feedback loop and an error detecting device called a differential. The feedback loop sends the magnitude of the output θ_o, back to the differential, which compares the output with the input. If there is a discrepancy between the input and output positions, an error signal, ϵ, equal to their difference, $\theta_i - \theta_o = \epsilon$, continues to keep the system in motion until $\theta_i = \theta_o$ ($\epsilon = 0$). This type of system is the most basic type of servomechanism and is called a position control servo.

It follows from Figure 2-2 that a servomechanism may be defined as a combination of elements for the control of a source of power in which the output of the system or some function of the output is fed back for comparison with the input, and the difference between these quantities is used in controlling the power.

θ_i - Input angular displacement
θ_o - Output angular displacement
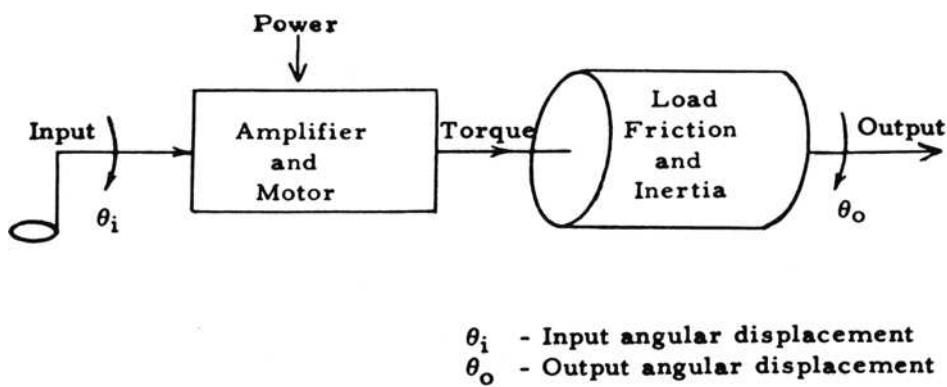
Fig. 2-1 Schematic of an open loop control system.
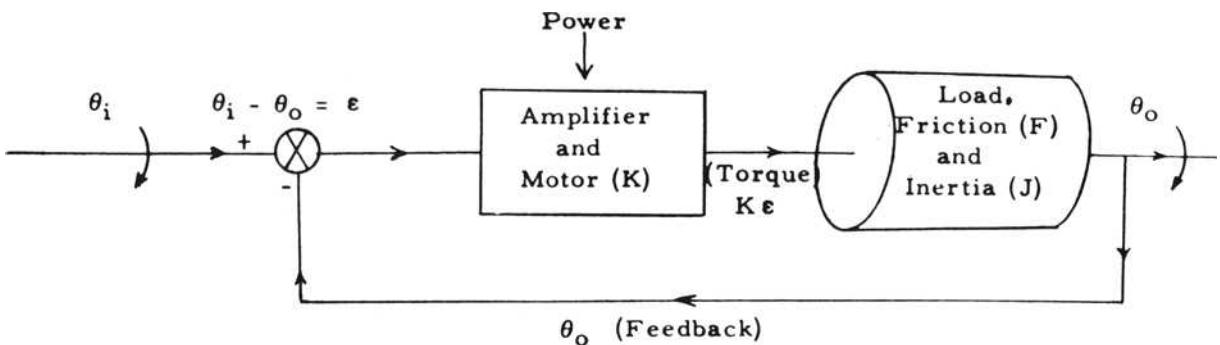
Fig. 2-2 Schematic of a closed loop control system.

In a closed loop system (servomechanism) if the output is not behaving properly by following θ_i, the physical system senses this at the input end and reacts by driving the output, θ_o, toward agreement with the input, θ_i. This advantage, of course, is not obtained without a price. Unless the system is properly designed with the elements correctly calibrated, the response time lag of the output may be excessive; the system may have excessive oscillations in the output; or the system may not even be stable (i.e., the output response may diverge and never approach the input).

2-3 ELEMENTS OF SERVOMECHANISMS

A servomechanism in its simplest form requires five basic elements:

(a) Input: The driving signal which initially activates the system, here considered as an angular position, with the designation θ_i. The input is considered as an angular position because many servomechanisms are used in conjunction with shaft rotation devices or aerodynamic control surface deflections. (This does not preclude servocontrol of variables other than angular position.)

(b) Differential: Error detecting device which mechanically or electrically subtracts the output from the input and determines the magnitude and direction of the error signal, ϵ, where $\epsilon = \theta_i - \theta_o$.

(c) Controller: Power amplifier and servo motor combination. The controller acts upon the error signal, ϵ, from the differential, driving and positioning the output. The magnitude of the amplification will be K, therefore the error signal, ϵ, goes into the controller, and $K\epsilon$, a torque, which may move a load, comes out.

(d) Output: Load or mechanism which is positioned to correspond to a given input. Its motion will also be considered to be an angular displacement, designated as θ_o.

(e) Feedback: The process (and component) which detects the actual amount of output displacement and sends a signal proportional to this amount back to the differential for comparison with the input. Feedback may be accomplished either mechanically or electrically.

2-4 SYSTEM ANALYSIS

The standard approach to servo theory is through mathematical analysis. This involves developing the equation which describes the system in terms of input and output, and then solving the equation for given inputs to determine the response. A typical input signal might be a step function, ramp function, sinusoidal function, or pulse function. The equation of a

system is obtained by equating the accelerating forces (or torques) to the decelerating forces (or torques) that act on the system (Figure 2-2).

(a) Accelerating torque. The only accelerating torque in this system is $K\epsilon$, the torque produced by the controller.

(b) Decelerating torque.

(1) Inertia torque: The load has mass and hence acts to retard the response of the output. It is proportional to the acceleration of the output and designated $J\ddot{\theta}_0$ where J is moment of inertia of the load, and

$$\ddot{\theta}_0 = \frac{d^2\theta_0}{dt^2}$$

(2) Friction torque: The viscous friction proportional to output velocity. It is due to friction between lubricated surfaces, such as gears and bearings. As will be seen, a certain amount of this retarding force may be desirable and certain devices such as fluid dashpots are sometimes introduced into the system to improve response. The torque due to viscous friction, whether inherent or added, is designated $F\dot{\theta}_0$ where F is the friction torque per unit speed, and

$$\dot{\theta}_0 = \frac{d\theta_0}{dt}.$$

Equating the above accelerating torque to the decelerating torques produces the equation of motion, in terms of the error signal ϵ, and the output, θ_0. This is a second order linear differential equation with constant coefficients of the form:

$$K\epsilon = J\ddot{\theta}_0 + F\dot{\theta}_0 \qquad (2\text{-}1)$$

But

$$\epsilon = \theta_i - \theta_0$$

so

$$J\ddot{\theta}_0 + F\dot{\theta}_0 = K(\theta_i - \theta_0)$$

or

$$J\ddot{\theta}_0 + F\dot{\theta}_0 + K\theta_0 = K\theta_i \qquad (2\text{-}2)$$

Equation (2-2) is the general equation of motion of a position control servo. The equation relates the output acceleration, velocity, and position to the input position. Note that this is mathematically the equation encountered in electricity which describes the behavior of a circuit containing inductance, resistance, and capacitance. It is also the equation describing the motion of a mass, damper, and spring in mechanics. The only difference is in the interpretation of the symbols.

In order to state (2-2) in even more general terms, the following definitions will be introduced:

$$\omega_n = \sqrt{\frac{K}{J}} \qquad (2\text{-}3)$$

$$\zeta = \frac{F}{2\sqrt{KJ}} \qquad (2\text{-}4)$$

The term ω_n in (2-3) is defined as the undamped natural frequency. It is the resonant frequency in radians per second at which a frictionless system will oscillate.

The term ζ (zeta) in (2-4) is defined as the damping ratio. It is a dimensionless constant which indicates the relative amount of damping, or viscous friction, in a system.

By substituting ζ and ω_n for the constant coefficients of (2-2), a completely general equation of motion of any second-order linear system is obtained.

$$\frac{1}{\omega_n{}^2}\ddot{\theta}_0 + \frac{2\zeta}{\omega_n}\dot{\theta}_0 + \theta_0 = \theta_i \qquad (2\text{-}5)$$

The proof of this substitution is left as an exercise.

2-5 RESPONSE TO A STEP INPUT

A step input is defined as an instantaneous jump to a new and constant position. For example, an instantaneous rotation of the input shaft in Figure 2-2 through 90° would be a step input of angular position. Figure 2-3 illustrates a general step input plotted against time.

$$\theta_i(t) = 0 \text{ for } t < 0$$
$$\theta_i(t) = A \text{ for } t > 0$$
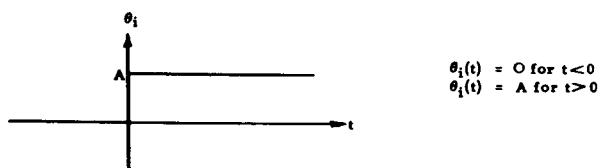
Fig. 2-3 Step function.

For a step input of $\theta_i = A$, the servo will drive the output until $\theta_0 = \theta_i = A$, or in other words, until there is no steady state error. However, before arriving at the steady value, A, the output must first experience a transient or intermediate response since no physical system is capable of an instantaneous jump through space. This transient response may take one of several forms, depending primarily on the magnitude of ζ, the damping ratio.

(a) $\zeta < 1$: The output is underdamped and will oscillate one or more times about the steady position A.

(b) $\zeta = 1$: The output is critically damped and will curve smoothly into A on an exponential path.

(c) $\zeta > 1$: The output is overdamped and will curve more slowly, but still smoothly, into A.

(d) $\zeta = 0$: The output is undamped and will oscillate on a sine wave at a frequency, ω_n.

(e) $\zeta < 0$: The system is negatively damped, is unstable, and will ultimately destroy itself in ever increasing wild gyrations.

From the preceding list, the advantage of rewriting the equation of motion in the form of

(2-5) is clear. A qualitative analysis of the system may be quickly made without resorting to a rigorous solution of the differential equation. A quantitative analysis requires either a mathematical solution or a graphical solution with the aid of an analog computer. In Figure 2-4 responses to step inputs are shown for each of the ranges of the damping ratio described above. The analog computer solution is the subject of the next chapter.
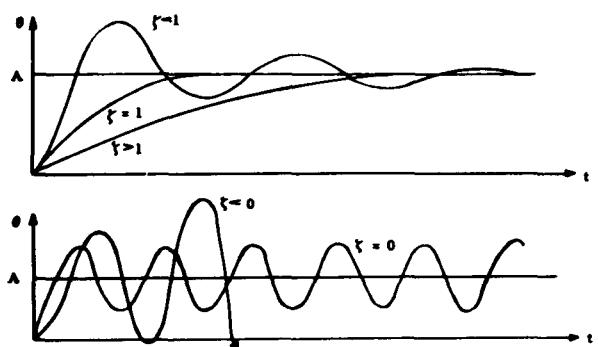
Fig. 2-4 Responses to step input, $\theta_i = A$.

2-6 RESPONSE TO A RAMP INPUT

Another type of input which is perhaps even more frequently encountered is the ramp input; that is, one which varies with time at a constant rate. This could be represented by a man turning a handwheel at a constant angular speed, ω_i. Figure 2-5 illustrates a general ramp input plotted against time.

For a ramp input of $\theta_i = \omega_i t$, the servo will attempt to drive the output until $\theta_0 = \theta_i$, but, due to the inherent inertia of the system, the output can never quite catch up to the input. After the transient effect has died out a steady state error, or time lag, will remain and the output will follow along behind the input.

In order to determine just what amount of lag will be present, it will be necessary to solve for the steady state response. The equation of motion is first rewritten in terms of operator (p) notation, as follows.

$$\text{Let } p\theta_0 = \frac{d\theta_0}{dt} = \dot{\theta}_0$$

$$p^2\theta_0 = \frac{d^2\theta_0}{dt^2} = \ddot{\theta}_0$$

then

$$\frac{1}{\omega_n^2} p^2\theta_0 + \frac{2\zeta}{\omega_n} p\theta_0 + \theta_0 = \theta_i \qquad (2\text{-}6)$$
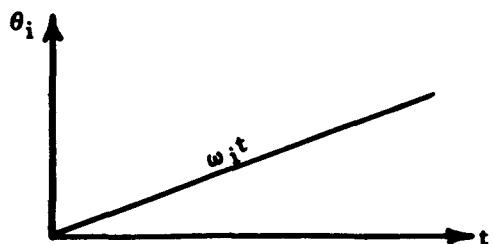
Fig. 2-5 Ramp function.

or

$$\left(\frac{1}{\omega_n^2} p^2 + \frac{2\zeta}{\omega_n} p + 1\right) \theta_0 = \theta_i \qquad (2\text{-}7)$$

Solving (2-7) for θ_0:

$$\theta_0 = \frac{1}{\dfrac{1}{\omega_n^2} p^2 + \dfrac{2\zeta}{\omega_n} p + 1} \theta_i \qquad (2\text{-}8)$$

By long division the right side of (2-8) may be converted to an infinite power series in p.

$$\theta_0 = \left(1 - \frac{2\zeta}{\omega_n} p + \frac{4\zeta^2 - 1}{\omega_n^2} p^2 + \ldots\right) \theta_i \qquad (2\text{-}9)$$

Applying (2-9) to the ramp input, $\theta_i = \omega_i t$, the steady state output becomes,

$$\theta_0 = \left(1 - \frac{2\zeta}{\omega_n} p\right) \omega_i t$$

($p^2 \omega_i t$ and higher terms are zero)

or

$$\theta_0 = \omega_i t - \frac{2\zeta}{\omega_n} \omega_i = \omega_i \left(t - \frac{2\zeta}{\omega_n}\right) \qquad (2\text{-}10)$$

The output will then lag behind the input by $\dfrac{2\zeta}{\omega_n}$ seconds in time, or $\dfrac{2\zeta}{\omega_n} \omega_i$ radians in position. Equation (2-10) indicates that a system with zero damping ($\zeta = 0$) will have no lag, but such a system will oscillate indefinitely and so is not practical. In Figure 2-6 responses to ramp inputs are shown, again for each of the ranges of the damping ratio.

2-7 METHODS OF IMPROVING SYSTEM RESPONSE

The basic servomechanism uses a control signal which is proportional to the difference of the input and output signals. This type of servo is commonly called a position servo, since it compares only the positions of the input and output.

In an analysis, the most descriptive parameter was found to be

$$\zeta = \frac{F}{2\sqrt{JK}}.$$

As ζ increases, the response becomes more sluggish and less oscillatory. An optimum servo control system should have a very rapid speed of response, and very little oscillation, or hunting. In practice, it has been found that ζ should generally lie in the range of 0.3 to 1.0.

The system moment of inertia J, is usually fixed, which leaves F and K as variables. Decreasing K, the controller gain, reduces the available output torque $K\epsilon$, used to drive the system, so K should be as large as possible. The viscous friction, F, is usually a rather small quantity in a well designed system, since losses due to friction are not desirable. A small F and a large K indicate that ζ will be a small quantity, i.e., the system will be highly oscillatory, and there is apparently nothing that can be done about it. However, there are techniques available which add artificial damping; two of these methods will now be described.

2-7.1 DERIVATIVE FEEDBACK

In this scheme we feed back not only the output position, but also the output velocity multiplied by a suitable constant, so that we have position plus velocity control. The velocity is obtained by taking the first time derivative of the output, hence, the name derivative feedback.

Using the technique developed for (2-2), the equation of motion of the derivative feedback servo becomes:

$$J\ddot{\theta}_0 + (F + KC_d)\dot{\theta}_0 + K\theta_0 = K\theta_i \qquad (2\text{-}11)$$

so that now

$$\zeta = \frac{F + KC_d}{2\sqrt{JK}},$$

and the damping ratio has been effectively
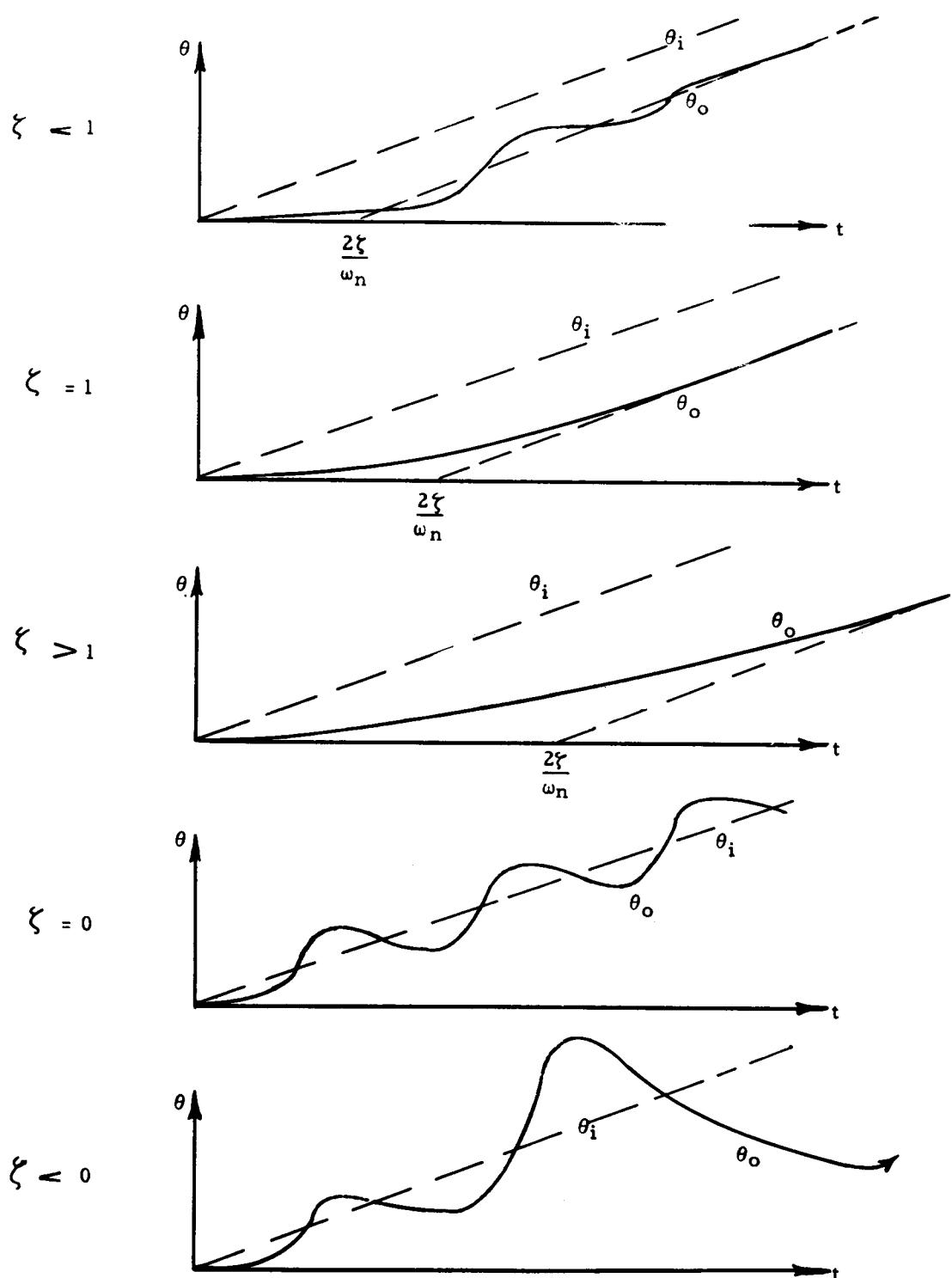
Fig. 2-6 Responses to ramp input, $\theta_i = \omega_i t$.
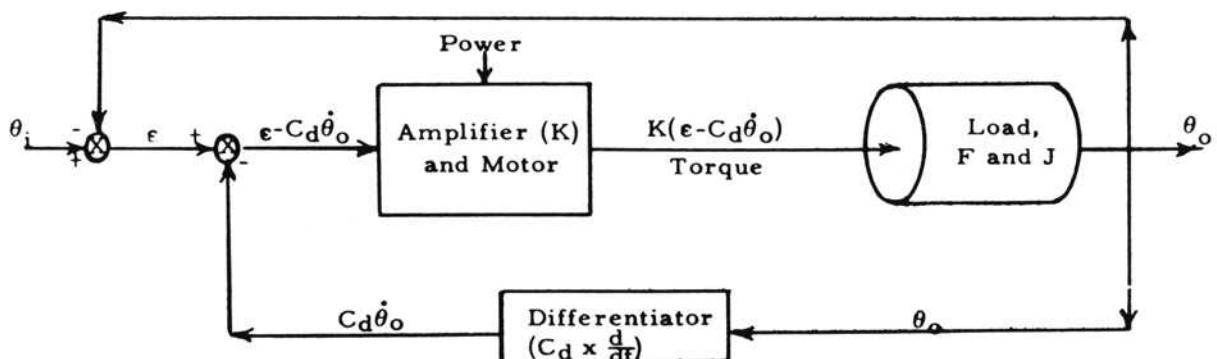
Fig. 2-7 Derivative feedback servo.
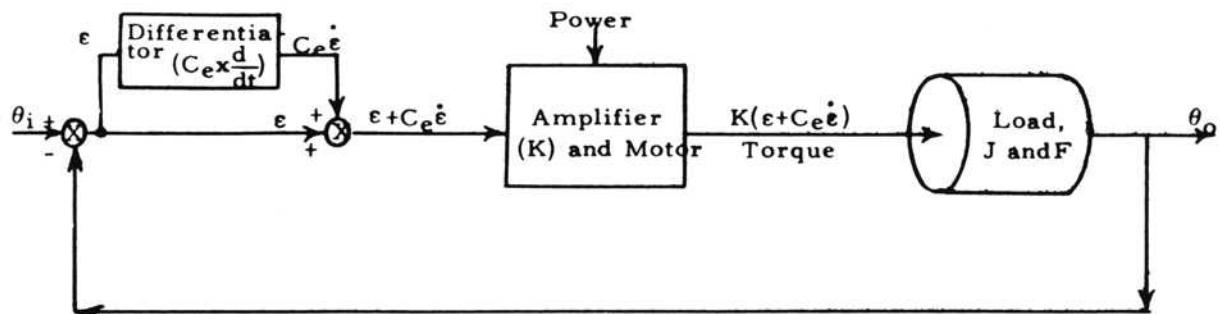
Fig. 2-8 Error-rate control servo.

increased without dissipating additional energy through friction. Using derivative feedback it is theoretically possible to operate a system with zero friction (F) and still maintain sufficient damping for proper control.

2-7.2 ERROR-RATE CONTROL

In this scheme the output position is fed back, as in position control, but the error signal produced is differentiated to produce an error-rate signal. The input to the controller is the sum of the error signal and the error-rate signal.

The equation of motion of this device is:

$$J\ddot{\theta}_0 + (F + KC_e)\,\dot{\theta}_0 + K\theta_0 = KC_e\,\dot{\theta}_i + K\theta_i \quad (2-12)$$

so that now

$$\zeta = \frac{F + KC_e}{2\sqrt{JK}},$$

and again the damping ratio has been effectively increased.

2-7.3 INTEGRAL CONTROL

The improvement in response with the use of

derivatives next leads to an investigation of response with the use of integrals. As in error-rate control, output position is fed back to obtain an error signal, then position error plus the integral of error is used as an input to the controller.

The equation of motion of this system is,

$$J\ddot{\theta}_0 + F\dot{\theta}_0 + K\theta_0 + KC_i \int \theta_0 dt = K\theta_i + KC_i \int \theta_i dt \quad (2-13)$$

Differentiating once,

$$J\dddot{\theta}_0 + F\ddot{\theta}_0 + K\dot{\theta}_0 + KC_i\theta_0 \doteq K\dot{\theta}_i + KC_i\theta_i \quad (2-14)$$

This equation now represents a third order differential equation, for which ζ and ω_n can no longer be defined. A mathematical solution and a computer analysis will show that the transient response of this system becomes increasingly oscillatory as the integral constant C_i is increased. Ultimately, for large values of C_i, the system becomes completely unstable.

The steady-state solution, however, can readily
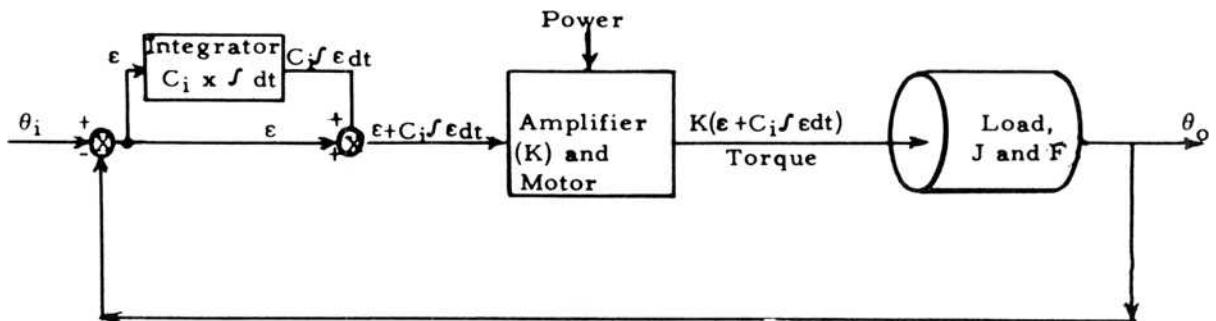
Fig. 2-9 Integral control servo.

be determined by use of the operator-division process outlined in Par. 2-7. The result is (2-15).

$$\theta_0 = \left(1 - \frac{F}{KC_i} p^2 + \ldots\right) \theta_i \qquad (2\text{-}15)$$

The surprising conclusion drawn from (2-15) is that for ramp inputs, as well as for step inputs, there will be no steady state error, i.e., no lag in the response. This removal of lag is, therefore, the most important trait of an integral control system.

If, as often occurs, the addition of integral control creates too much oscillation in the system output, the further addition of error-rate control will provide sufficient artificial damping for stable operation. Such multiple, or compound, control systems are, of course, much more complicated and are beyond the scope of an introductory lesson on servomechanisms.

2-8 SUMMARY

The necessary ingredients for a servomechanism are:

(a) An external power supply which is to be controlled.

(b) A feedback device which provides an error signal.

(c) An amplifier which drives a motor which, in turn, sets the output at a desired position.

Without the feedback device we would have an open loop system with its inherent disadvantage of inaccuracy. With feedback we have a servomechanism with greater accuracy, speed of response, and flexibility.

A servo can become unstable under certain conditions. However, with the addition of compensating elements, such as integrators or differentiators, stability is restored and overall response is vastly improved. The basic servomechanisms are described in terms of second-order linear differential equations which may be easily solved by either classical mathematics or modern computing machinery. By varying the constants of these equations and observing the effect on system response, a control system designer is able to build a device which will satisfy his requirements. For example, he may want a system capable of holding a missile on a prescribed course; or of maintaining a chemical process at a certain temperature; or of rotating a gun turret to a desired heading. For each requirement a different design problem must be solved.

(a) Position control:

$$\theta_0 = \left(1 - \frac{2\zeta}{\omega_n} p + \ldots\right) \theta_i$$

No steady error for step inputs.

$\dfrac{2\zeta}{\omega_n}$ seconds lag for ramp inputs.

(b) Derivative feedback:

$$\theta_0 = \left[1 - \left(\frac{2\zeta}{\omega_n} + C_d \right) p + \ldots \right] \theta_i$$

No steady error for step inputs.

$\frac{2\zeta}{W_n} + C_d$ seconds lag for ramp inputs.

Artificial damping introduced.

(c) Error-rate control:

$$\theta_0 = \left(1 - \frac{2\zeta}{\omega_n} p + \ldots \right) \theta_i$$

No steady error for step inputs.

$\frac{2\zeta}{\omega_n}$ seconds lag for ramp inputs.

Artificial damping introduced.

(d) Integral control:

$$\theta_0 = \left(1 - \frac{F}{KC_i} p^2 + \ldots \right) \theta_i$$

No steady error for step or ramp inputs.

REFERENCES

1 *Advanced Course I for Upper Sections,* West Point, New York: Dept. of Electrical Engineering, USMA, 1958, Part I.

2 Bruns and Saunders, *Analysis of Feedback Control Systems,* McGraw-Hill Book Company, Inc., N.Y., 1955.

3 Walter R. Evans, *Control-System Dynamics,* McGraw-Hill Book Company, Inc., N.Y., 1954.

4 James, Nichols, and Phillips, *Theory of Servomechanisms,* McGraw-Hill Book Company, Inc., N.Y., 1947.

CHAPTER 3

ELECTRONIC COMPUTERS

3-1   INTRODUCTION

World War II provided a tremendous stimulus for the expansion of a great many fields of science. By no means the least of these was the development of electronic computers. This development followed two basic lines: one, the logical conversion of existing mechanical digital computers into their electronic counterpart, and the other, the growth of the entirely new electronic analog computer. The development of modern, complex weapon systems would be virtually impossible if electronic computers were not available. All guided missiles use either analog or digital computers for trajectory calculations. Designers of weapons depend upon the speed, accuracy, and economy of computers in developing reliable items of equipment. The list of possible applications of both analog and digital computers grows almost daily and has no foreseeable limit. The following sections will present the characteristics and applications of each, and will conclude with a comparison of both.

3-2   ELECTRONIC ANALOG COMPUTERS

The electronic analog computer, often called the electronic differential analyzer (EDA), is a direct outgrowth of the M-9 gun director developed during World War II by the Bell Telephone Laboratories. In 1947, the circuits developed for the M-9 were first applied to an actual laboratory computing device. Since that time the analog computer has become an essential tool for dynamic analysis.

The chief characteristic of the EDA is the fact that it uses voltages to represent the variables of a problem. The types of problems best suited for the EDA are those which involve the solution of simultaneous differential equations, either linear or nonlinear, and with either constant or variable coefficients. However, the machine is not limited to this range. It can also handle transcendental ($\sin X$, $\log X$, e^x) functions with equal ease. The output of the computer is generally a continuous graphical plot of the variables which allows the operator to visualize quite easily the output of the physical system he is investigating. As an example, consider the equation of motion of a body with a varying velocity:

$$X = \int_0^t V dt \qquad (3-1)$$

To solve this equation on an EDA, the variables X and V would be represented by voltages. The input V, would be electronically integrated, and the output X, would be automatically plotted graphically as a function of time. The graph would indicate how the position of the body varied with time.

3-2.1   THE OPERATIONAL AMPLIFIER

The basic component, or building block, of any electronic analog computer is the operational amplifier, first used in the M-9 gun director. The circuit diagram of the amplifier is shown in Figure 3-1.

The operational amplifier is a high gain d-c amplifier which uses an input impedance, Z_i, in series, and a feedback impedance, Z_f. Two assumptions are required to analyze the circuit: (1) the gain of the amplifier is very large; and (2) the grid current into the amplifier from point P is negligible.

3-1
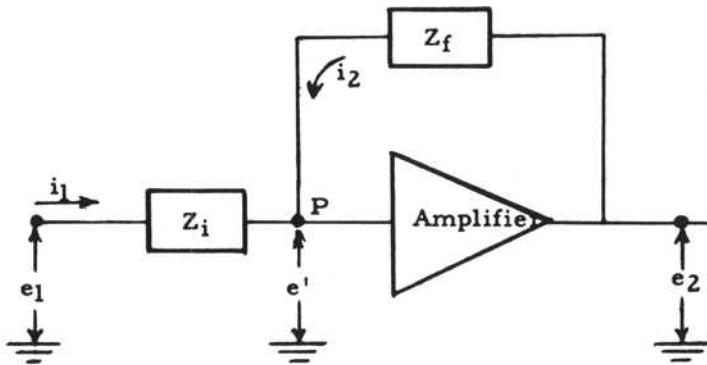
Fig. 3-1 Operational amplifier.

The current through Z_i is

$$i_1 = \frac{e_1 - e'}{Z_i},$$

and the feedback current is

$$i_2 = \frac{e_2 - e'}{Z_f}.$$

Since the sum of the currents into a point must be zero, we obtain:

$$\frac{e_1 - e'}{Z_i} + \frac{e_2 - e'}{Z_f} = 0 \tag{3-2}$$

Let the amplifier gain be $-A$ so that

$$e_2 = -Ae'. \tag{3-3}$$

Substituting (3-3) into (3-2),

$$\frac{e_1 + \dfrac{e_2}{A}}{Z_i} + \frac{e_2 + \dfrac{e_2}{A}}{Z_f} = 0 \tag{3-4}$$

$$-\frac{Z_f}{Z_i} e_1 = \left(\frac{Z_f}{AZ_i} + 1 + \frac{1}{A} \right) e_2 \tag{3-5}$$

$$-e_2 = \frac{Z_f}{Z_i} e_1 \left[\frac{1}{1 + \dfrac{1}{A}\left(1 + \dfrac{Z_f}{Z_i} \right)} \right] \tag{3-6}$$

Equation (3-6) is the general relationship between the input and output voltages of the amplifier. An extremely useful approximation is made using the first assumption, that the gain A is very large, or more precisely, that the gain is very large compared to the quantity $\left(1 + \dfrac{Z_f}{Z_i} \right)$.

Ordinarily the amplifier gain is greater than 5000, so that (3-6) may be written:

$$e_2 = -\frac{Z_f}{Z_i} e_1. \tag{3-7}$$

Note that the operational amplifier reverses the sign of the input voltage and also provides a method of multiplying the input voltage by the ratio $\dfrac{Z_f}{Z_i}$.

3-2.2 SUMMING AND INTEGRATING CIRCUITS

If Z_i and Z_f are both pure resistances, R_i and R_f, then

$$e_2 = -\frac{R_f}{R_i} e_1 \tag{3-8}$$

and one is able to multiply by any desired constant, provided that $\left(1 + \dfrac{R_f}{R_i} \right)$ is much less than A, the amplifier gain.

If Z_i is a resistance, R_i, and Z_f is a capacitance, C_f,

$$e_2 = \frac{1}{-\dfrac{p\,C_f}{R_i}} e_1 = -\frac{1}{pR_iC_f} e_1, \tag{3-9}$$

(using the operational notation of Chapter 2,
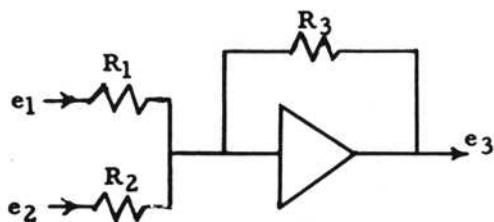
$$e_3 = -\left(\frac{R_3}{R_1} e_1 + \frac{R_3}{R_2} e_2\right)$$

Fig. 3-2   Summing amplifier.
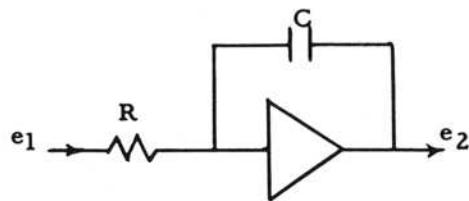
$$e_2 = -\frac{1}{RC} \int_0^t e_1 dt$$

Fig. 3-3   Integrating amplifier.

where $p\theta = \dfrac{d\theta}{dt}$ and $\left(\dfrac{1}{P}\right) \theta = \int_0^t \theta dt)$ which also may be written:

$$e_2 = -\frac{1}{R_i C_f} \int_0^t e_1 dt \qquad (3\text{-}10)$$

and one is able to integrate the input, in addition to multiplying by a constant and changing sign.

Many other circuit arrangements are possible using combinations of resistance, capacitance, and inductance, but not all are practical. By using only the two circuits described above, any linear differential equation may be solved. Figures 3-2 and 3-3 illustrate the circuits used. It should be noted that voltages introduced on parallel input resistances are added by the amplifier.

3-2.3   SOLUTION OF A DIFFERENTIAL EQUATION

The technique of devising a wiring diagram which will solve a given equation is best shown by an example. Refer to (2-2) of the preceding chapter (Control Systems). This is a general linear second-order differential equation, a type frequently encountered in the analysis of dynamic systems. The equation is repeated below.

The wiring diagram developed here will be utilized in Chapter 10 in the design analysis of a machine gun.

$$J\ddot{\theta}_0 + F\dot{\theta}_0 + K\theta_0 = K\theta_i, \qquad (3\text{-}11)$$

The first step in finding the wiring diagram, or computer circuitry, is to solve (3-11) for the highest derivative; in this case, $\ddot{\theta}_0$.

$$\ddot{\theta}_0 = -\frac{F}{J} \dot{\theta}_0 - \frac{K}{J} \theta_0 + \frac{K}{J} \theta_i, \qquad (3\text{-}12)$$

First, assume a voltage representing $\ddot{\theta}_0$ is available. This voltage is integrated twice to obtain first $\dot{\theta}_0$ and then θ_0. For this operation, two integrating operational amplifiers are used.

The numbers above each resistance indicate their value in megohms, while the numbers above each capacitance indicate microfarads. From Figure 3-3, the multiplications factor, $\dfrac{1}{RC}$, becomes $\dfrac{1}{10^6 \times 10^{-6}} = 1$, so the integrators of Figure 3-4 will change sign and integrate without multiplication.

Voltages now are available which are proportional to the variables of the equation; but we only assumed that $\ddot{\theta}_0$ was available originally. If
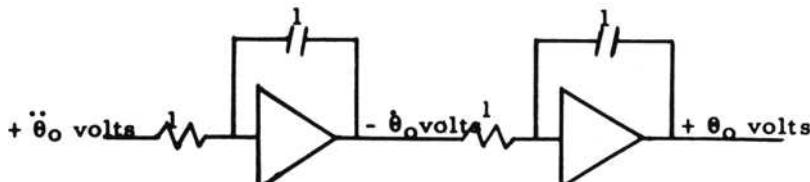
Fig. 3-4   Double integration circuit.
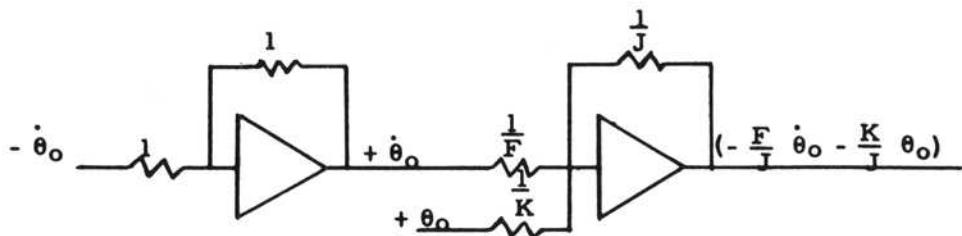
Fig. 3-5 Multiplication and summation circuit.
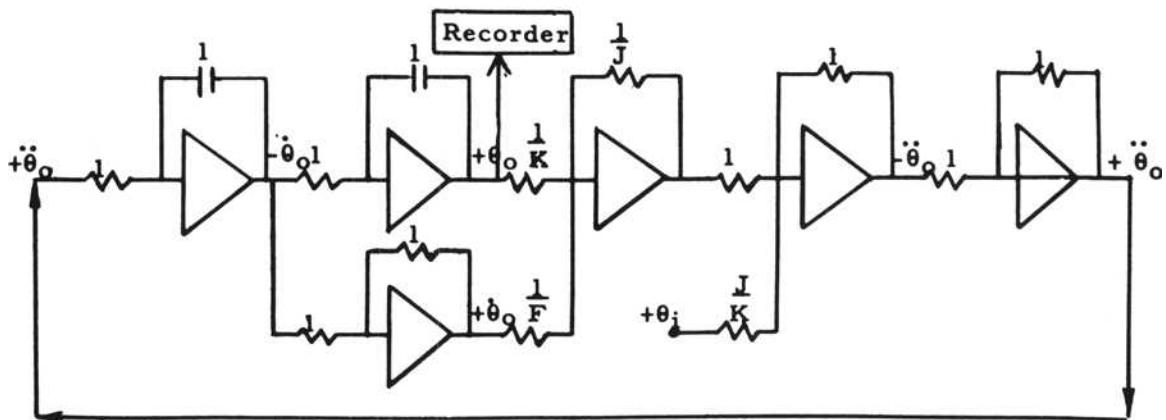
Fig. 3-6 EDA circuit for the solution of a second order equation.

$\ddot{\theta}_0$ is replaced by the three quantities appearing on the right side of (3-12), then one should still be able to integrate twice to obtain, progressively, $\dot{\theta}_0$ and θ_0. But these are precisely the quantities needed to obtain $\ddot{\theta}_0$, so the circuit is apparently going in circles, which is exactly what must be done. Since $-\dot{\theta}_0$ is available, and $-\dfrac{F}{J}\dot{\theta}_0$ is needed, and also since θ_0 is available, and $-\dfrac{K}{J}\theta_0$ is needed, the next step is to multiply by the appropriate constants, changing signs as necessary.

The output voltage of Figure 3-5 is still only part of the right side of (3-12). To this voltage we must now add the input voltage $\dfrac{K}{J}\theta_i$, and again change signs so that the final output will be θ_0, from (3-12).

By combining the circuits of Figures 3-4 and 3-5 and adding the voltage $\dfrac{K}{J}\theta_i$ as indicated, the circuit shown in Figure 3-6 is obtained. Note that at each end of the circuit there is a voltage equal to $\ddot{\theta}_0$. The logical step to complete the circuit is to hook both ends together, thereby justifying the original assumption that $\ddot{\theta}_0$ would be, and is, available for integration.

The output voltage representing angular position (θ_0) is fed into a recording device and plotted against time to give a graphical picture of the manner in which the physical system behaves. In a similar manner the voltage $\dot{\theta}_0$ could be plotted to illustrate the angular velocity of the system.

Obtaining a wiring diagram may appear to be a tedious operation at first, but it should be remembered that the preceding steps are general, and once mastered can be applied to a new problem in a very few minutes. The final diagram indicates that an EDA circuit is a closed loop network, and as such, is ideally suited to the analysis of servomechanisms. In general, then, the electronic analog computer is best utilized in

the solution of dynamic problems, that is, those involving equations of motion. The accuracy of the solution will, of course, depend largely on the accuracy of the computer components and the ability of the operator. Under optimum conditions the accuracy can be extended to four or five significant figures, which is generally more than sufficient for most applications. Where greater precision is required, one must turn to the electronic digital computer.

3-3 DIGITAL COMPUTERS

Digital computers have been in use since man first learned to count on his fingers. Throughout history this ability to represent objects with digits has evolved into the use of the abacus, the adding machine, the desk calculator, the mechanical digital computer, and, finally, in this century, the high speed electronic digital computer. The various devices are identical in one respect. They all represent data as discrete whole number values, whether it is by counting fingers, beads, gear teeth, or electrical impulses.

Before any discussion of the operation of digital computers, it would be well to define what is meant by a number system. A number system refers to the number of individual digits used. For example, we normally use a number system of base 10, which means we employ ten different digits (0 through 9) to write any given number. This convention was undoubtedly established solely because the human hands were endowed with ten fingers. It is entirely probable that, had we been given a different number of digits, our number system would again correspond.

The majority of the digital computers in use are built around a number system of base 2, i.e., they use only the digits 0 and 1. The reason behind this choice is obvious when one realizes that the computers operate on pulses which are either present or not present. A pulse represents the number 1 and no pulse represents the number 0. The problem that now arises is that of converting our familiar decimal system to the simple binary system of the computer.

The solution of this problem is best obtained by an example. Given the decimal number 137, find its binary equivalent. The number 137 may be broken down into three digits (1, 3, and 7) each of which must be multiplied by a power of ten to determine the relative position of the digits. In equation form this becomes:

$$137 = (1 \times 10^2) + (3 \times 10^1) + (7 \times 10^0) \quad (3\text{-}13)$$

A generalization produces the following:

$$N = (d_n \times 10^n) + (d_{n-1} \times 10^{n-1}) + \dots$$
$$+ (d_1 \times 10^1) + (d_0 \times 10^0) \quad (3\text{-}14)$$

Note that in general, the appropriate digit is multiplied by a corresponding power of the base 10. In the decimal system, the digits (d) may be any number from 0 to 9. In the binary system, the digits may be only the numbers 0 or 1, and the base is 2. A general binary equation of a number (N) is then:

$$N = (d_n \times 2^n) + (d_{n-1} \times 2^{n-1}) + \dots$$
$$+ (d_1 \times 2^1) + (d_0 \times 2^0) \quad (3\text{-}15)$$

The decimal number 137 may be broken into several numbers, all of which are powers of two.

$$137 = 128 + 8 + 1 = 2^7 + 2^3 + 2^0$$

By similar reasoning, any decimal number may be written as the sum of certain powers of two. Using (3-15) with $d_7 = 1$, $d_3 = 1$, $d_0 = 1$, and all other digits zero, we may write our decimal number 137 in binary form as follows:

$$137 = (1 \times 2^7) + (0 \times 2^6) + (0 \times 2^5) + (0 \times 2^4)$$
$$+ (1 \times 2^3) + (0 \times 2^2) + (0 \times 2^1) + (1 \times 2^0)$$
$$= (1 \times 128) + (0 \times 64) + (0 \times 32)$$
$$+ (0 \times 16) + (1 \times 8) + (0 \times 4)$$
$$+ (0 \times 2) + (1 \times 1) \quad (3\text{-}16)$$

In the decimal system we wrote the digits 1, 3, 7 in descending order. In the binary system the same number is represented by eight digits instead of three. Writing the digits in descending order gives us:

$$137 = 10001001 \quad (3\text{-}17)$$

As an exercise, the student should prove that the following table is correct.

DECIMAL	BINARY
1	1
2	10
3	11
4	100
5	101
6	110
7	111
8	1000
9	1001
10	1010

The simplicity of the binary number system is demonstrated by the following tables, which represent the complete addition and multiplication tables for binary arithmetic.

ADDITION	MULTIPLICATION
$0 + 0 = 0$	$0 \times 0 = 0$
$0 + 1 = 1$	$0 \times 1 = 0$
$1 + 1 = 10$	$1 \times 1 = 1$

In the decimal system, numbers to the right of the decimal point are written in descending negative powers of ten. In the binary system, numbers to the right of the binary point are written in descending negative powers of two. For example, the decimal number 5.75 is written in binary notation as 101.11, which is $4 + 0 + 1 + \frac{1}{2} + \frac{1}{4}$. Examples of addition and multiplication are given by the following comparisons.

Addition:

DECIMAL		BINARY
5.75		101.11
+3.50	=	+ 11.10
9.25		1001.01

Multiplication:

DECIMAL		BINARY
5.75		101.11
× 3.5		× 11.1
2.875	=	10.111
17.25		101.11
20.125		1011.1
		10100.001

Using arithmetic operations such as these, the digital computer can carry out rapid calculations of unbelievable complexity by easily handling as many as 100,000 numbers per second. It is only necessary for the operator to instruct the machine, before the operation begins, as to what steps it should take to solve the problem at hand.

Even though most digital computers utilize the binary system for arithmetic operations, and the designer of such a machine must certainly have an understanding of this number system, it is not essential for the operator of the machine to know or use any system other than the ordinary decimal system. Most computers have an internal coding device which allows the operator to use the decimal system while the machine operates in the binary system. The machines are also quite capable of translating letters and words into binary numbers, so that instructions may be given in English. From the operator's viewpoint, the use of a digital computer involves only the preparation of a proper program to solve a particular problem. A program for a digital computer is an orderly sequence of instructions and data which guides the machine to a logical conclusion.

This program is normally fed into the machine by means of punch cards, magnetic tape, or electric typewriter. The information is stored in the memory of the computer on magnetic drums or tapes so that it will be quickly available when needed. Next, the numerical data are fed in and the computer is started. The machine now reads its first instruction, performs the required arithmetic operation, and goes on to the next instruction, following this sequence until the program is completed and the answer is obtained. From this brief description it can be seen that a digital computer must contain the five following components:

(1) Input-output unit.

(2) Data storage or memory unit.

(3) Arithmetic unit for actual computation.

(4) Transfer unit for moving data from the memory to the arithmetic unit and back.

(5) Controller for sequencing the operations specified by the program.

The solution of any problem is completely dependent on the use of a correct program. To eliminate errors and provide a logical general approach, the programmer should always follow the four steps listed below.

(1) State the problem.

(2) Write a mathematical model of the problem.

(3) Construct a flow diagram of the desired program.

(4) Write the final program for the machine.

A simple example will be given to illustrate these steps.

(1) Statement: If the statistics of the Army-Notre Dame game and the Navy-Notre Dame game are known, who will win the Army-Navy game? For each team we will find the difference in scores, add the yards gained per carry, and divide by two for the team wearing dark jerseys (dark jerseys are considered bad luck). The results will be compared and BEAT NAVY printed on a punch card if Army is to win; otherwise NEXT YEAR will be printed on a punch card.

(2) Model:

MEMORY CELL NUMBER	CONTENTS OF CELL
001	Army score
002	Notre Dame score (against Army)
003	Army yards gained per carry
004	Navy score
005	Notre Dame score (against Navy)
006	Navy yards gained per carry
007	One or Two (depending on Army jerseys)
008	One or Two (depending on Navy jerseys)
009	BEAT NAVY
010	NEXT YEAR
011	(empty)
012	(empty)

If [(001 − 002 + 003) ÷ (007)] > [(004 − 005 + 006) + (008)], print 009, otherwise print 010.

(3) Flow Diagram:
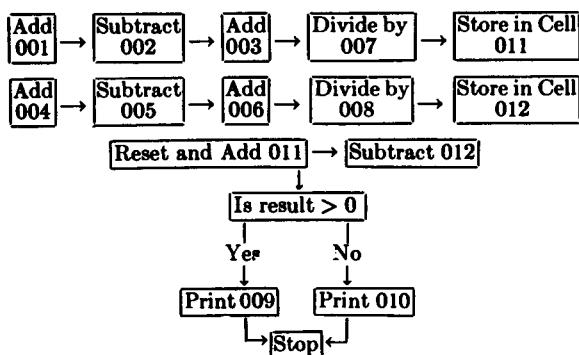
(4) Program:

CODE	MEANING
RSA	Reset and Add (clear arithmetic unit and add the contents of —)
ADD	Add to previous result the contents of —
SUB	Subtract from previous result the contents of —
DVD	Divide previous result by the contents of —
STR	Store result in indicated memory cell
JIM	Jump If Minus (if previous result is negative, jump to indicated instruction number)
PCH	Punch (print result on a punch card)
STP	Stop operation

Final Program:

INSTRUCTION NUMBER	CODE	CELL NUMBER
101	RSA	001
102	SUB	002
103	ADD	003
104	DVD	007
105	STR	011
106	RSA	004
107	SUB	005
108	ADD	006
109	DVD	008
110	STR	012
111	RSA	011
112	SUB	012
113	JIM	116
114	PCH	009
115	STP	
116	PCH	010
117	STP	

From this example it can be seen that even for such a simple problem a relatively large number of instructions is required. For problems of great complexity it is entirely probable that several hundred, or even several thousand different instructions will be necessary. To obviate this difficulty, modern computers are being designed with the ability to program themselves internally, given only the statement of the problem. This ability has obvious advantages of economy of time and money. In the past it has

sometimes required hundreds of man-hours to prepare a program which the computer can digest and solve in a few minutes of operation. It should be pointed out, however, that the preparation of the program should amount to a small fraction of the labor involved in manual solution of the same problem, or else the machine is of no practical use.

The digital computer is not limited to any specific type of problem. It is capable of solving any type of mathematical problem to any desired degree of precision. It can operate automatic factories, compute guided missile trajectories and correct the missile in flight, prepare payrolls or census figures, keep track of thousands of items in a warehouse, sort box cars, or prepare grade sheets. It has numerous applications in such fields as engineering, business, finance, transportation, and meteorology. The digital computer is also ideally suited to large scale, highly repetitive problems, such as the preparation of bombing and firing tables.

3-4   COMPARISON OF ANALOG AND DIGITAL COMPUTERS

At some point in the design of most complex weapon systems the question of whether to install analog or digital equipment frequently arises. Since either type of computer is capable of solving any soluble mathematical equation, the choice must hinge upon a number of specific requirements. In a general case there can be no clear cut advantage for one or the other. A number of outstanding differences and similarities will be discussed in order to outline the performance characteristics which will dictate the final choice.

3-4.1   ACCURACY

Accuracy may be defined as the number of significant figures obtainable which are in fact correct. Any significant figures obtained, for example, by rounding off or by eye interpolation are not considered accurate. An analog computer can seldom be made more accurate than three significant figures, which is more than adequate for a wide variety of applications. The digital computer is able to extend this degree of accuracy to any desired limit, but at the cost of size, speed, and complexity. Many present-day digital computers are accurate to twenty or more significant figures.

3-4.2   PRECISION

Precision may be defined as the number of significant figures obtainable, without regard to absolute correctness. For example, in reading the number 953 on a slide rule three place precision is obtained, but only two place accuracy. Precision, therefore, may equal or exceed accuracy. Analog computers seldom exceed four place precision, while digital computers, again, may be extended to any desired limit.

3-4.3   SPEED

The analog computer solves the problem completely the instant current begins to flow. The digital computer, on the other hand, calculates sequentially, not instantaneously. For example, an analog computer can perform any number of integrations and constant multiplications at the same time, while a digital computer must perform each operation one after the other. There are, however, many cases in which a digital machine can do the work of several analog machines simultaneously by a time sharing process. In practice, either computer may be designed to provide a required solution speed.

3-4.4   ADAPTABILITY

Since both machines are capable of solving any equation, a choice might be made on the basis of adaptability, or the ability to change over quickly to a new problem. If it is assumed that a new digital program has previously been prepared, it will require only a few seconds for the digital computer to begin a new problem. The analog computer, on the other hand, must be completely rewired and thoroughly checked

before a new operation can be performed. However, if the preparation of the program is included in the change-over time, the analog computer will very likely save considerable time.

3-4.5 COST

Generally, the initial outlay for a digital computer is many times the cost of a typical analog installation. In addition, if expansion is desired, analog equipment may be added piece-meal in small quantities, while a whole new digital installation would be required. There is a rough rule of thumb which states that with an analog computer more calculus operations per dollar are obtained, while with a digital computer more arithmetic per dollar is obtained. Certainly cost is an important consideration, but not an overriding one. There are many areas in which one computer or the other will obviously be the better choice by virtue of the type of problem to be solved.

In summary, the electronic analog computer, or differential analyzer, is composed of cascaded operational amplifiers coupled with resistive and capacitive circuits. Its operation is continuous and depends upon the representation of physical quantities with d-c voltages. The electronic digital computer is composed of logical circuits, memory devices, and transfer equipment. Its operation is discrete and depends upon the representation of physical quantities or data with finite numbers.

REFERENCES

1 *Advanced Course I for Upper Sections*, Part I, West Point, N.Y.: Dept. of Elect. Engr., USMA.

2 Millman and Taub, *Pulse and Digital Circuits*, New York: McGraw-Hill Book Co., Inc., 1956.

3 W. W. Soroka, *Analog Methods in Computation and Simulation*, New York: McGraw-Hill Book Co., Inc., 1954.

4 C. A. A. Wass, *Introduction to Electronic Analogue Computers*, New York: McGraw-Hill Book Co., Inc., 1955.

5 *An Introduction to Electronic Computers*, Newark, N.J.: Prudential Insurance Company of America, 1954.

CHAPTER 4

INERTIAL NAVIGATION

4-1 INTRODUCTION

In Chapter 5 of Part 2 (Ballistics) a variety of guidance techniques was described in terms of their effects on the exterior ballistics, or flight paths, of associated missiles. The approach used in that portion of the text was essentially a black box technique. In this chapter, emphasis will be placed on the principles of inertial navigation since inertial components are used, either par-tially or wholly, in nearly every missile system now under development.

The reference to missiles in no way limits the application of inertial components to unmanned vehicles. Many aircraft, ships, and submarines now use inertial navigation, and its application to land vehicles is not without merit.

4-2 INERTIAL GUIDANCE

An inertial guidance system is one which measures actual motion with respect to a set of fixed, or inertial, axes contained within the system. There are three basic sub-systems to consider: the integrating gyroscopes which main-tain the orientations of the inertial axes; the accelerometers which measure accelerations along mutually perpendicular axes; and the computer which monitors and directs the entire operation. Each of these sub-systems will be studied to determine its operating character-istics.

4-3 INTEGRATING GYROSCOPES

The first law of gyroscopic action is the princi-ple of rigidity in space. A gyro which is free to move in any direction will maintain its original orientation in space. Conversely, a gyro which is restrained in one or more directions will attempt to resist any overturning torque. This resistance gives rise to the second law, which is the law of precession. Any attempt to change the orientation of the spin axis will cause the gyro to precess, or move its spin axis at right angles to the applied torque so as to reduce the applied torque to zero. Figure 4-1 illustrates a gyro mounted in three gimbals, a so-called three-degree-of-freedom gyro, which will maintain the
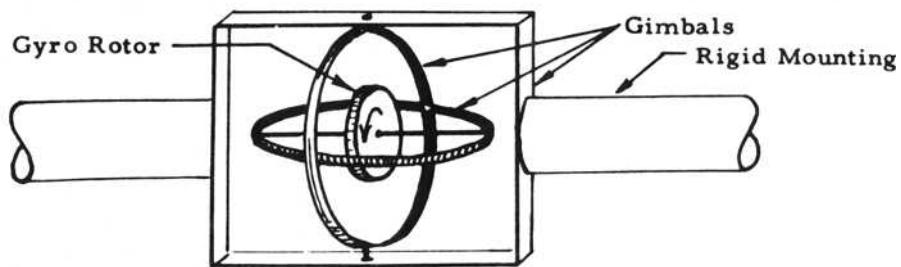
Fig. 4-1 Three-degree-of-freedom gyro.
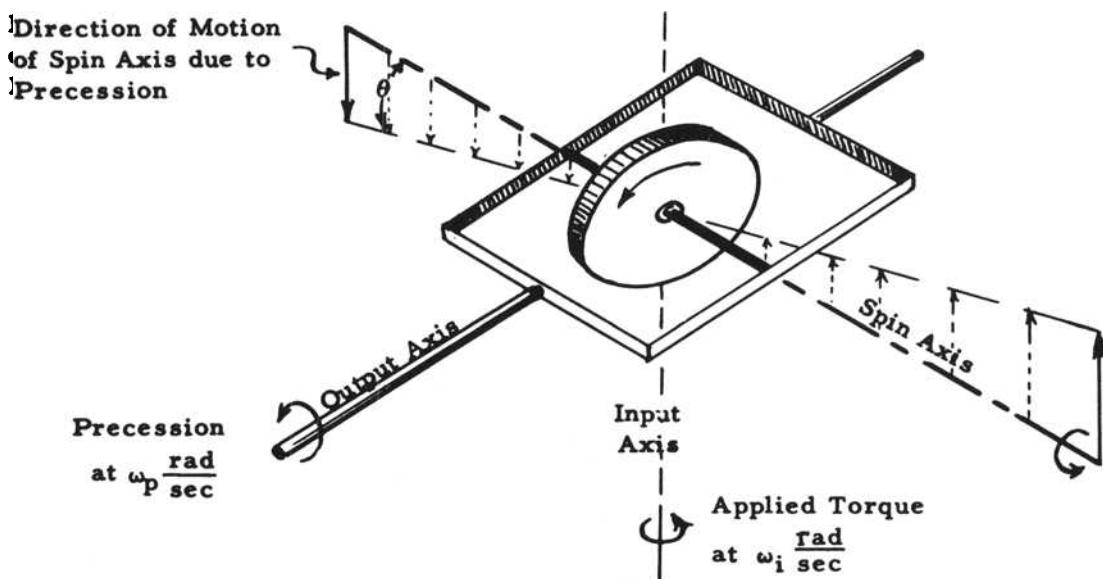
Fig. 4-2 Single-degree-of-freedom gyro.

orientation of its spin axis in space. The rigid mounting may be rotated in any direction without disturbing the gyroscope iself.

Figure 4-2 illustrates a single-degree-of-freedom gyro which is able to move in only one direction. An applied torque about the input axis will be resisted and will produce precession about the output axis. This precession will change the orientation of the spin axis.

The rate of rotation about the output axis due to precession is directly proportional to the rate of rotation about the input axis due to the applied torque, or $\omega_p = K\omega_i$, where K is a constant of proportionality and ω_p and ω_i are the angular rates defined in Figure 4-2. Since ω_p is the rate of change of θ, the angular position of the spin axis:

$$\frac{d\theta}{dt} = \omega_p = K\omega_i \qquad (4\text{-}1)$$

$$d\theta = K\omega_i \, dt \qquad (4\text{-}2)$$

$$\theta = K \int \omega_i \, dt \qquad (4\text{-}3)$$

From (4-3) it is seen that the single-degree-of-freedom gyro will actually integrate, thus the more common name of integrating gyro. If, around the output axis, a signal generator is

mounted which produces an electric signal proportional to the angle θ, any attitude change of a missile about the input axis will be translated into a voltage proportional to that change. The assembly, therefore, produces the first requirement for an analog computation, a voltage proportional to a physical quantity.

The assumption that the precessional rate is proportional to the angular input rate is only valid when the angle θ is at or very near zero. If θ is allowed to get too large (i.e., such that the approximation $\cos\theta = 1$ no longer holds), additional non-linear terms will be introduced due to cross-coupling effects. To keep θ at the null position, the output voltage from the signal generator is used to drive a motor, also on the output shaft, which will exactly balance the torque due to precession. Thus, very small output angles are produced keeping the system linear, while a voltage proportional to the integral of the input rate is still obtained. This voltage is therefore used to keep the three axes mutually perpendicular at all times.

In one commonly used commercial gyro, the gyro wheel and its spin motor are encased in a sealed cylindrical can. This can is, in turn, encased in a slightly larger oil filled can, so that the gyro case is free to rotate only about the common axis of the two cylinders. The spin axis
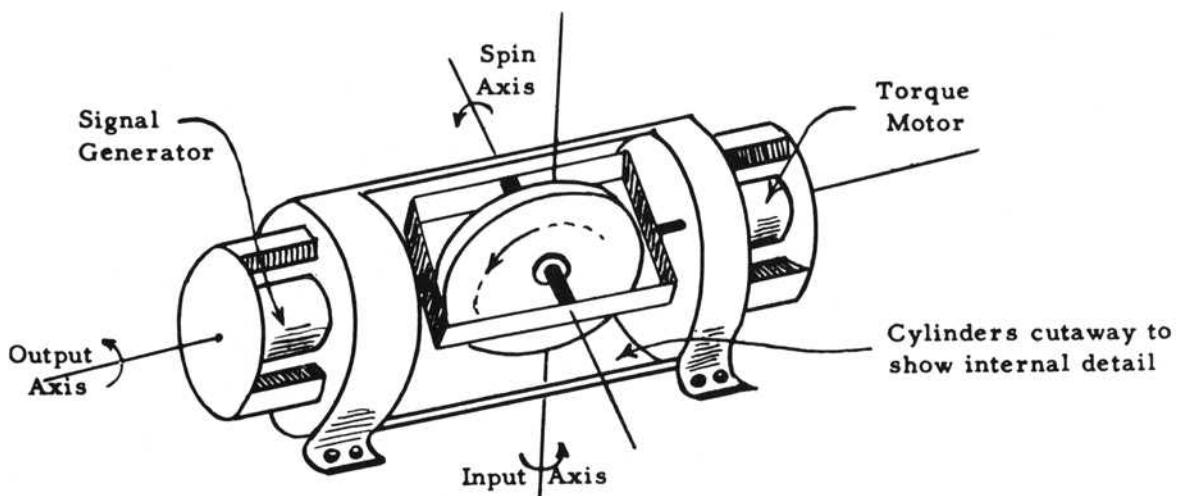
Fig. 4-3 Integrating gyro assembly.

of the gyro is at right angles to the axis of the cylinders. The signal generator and the torque motor are mounted on the axis of the cylinders, which is the output axis. The whole unit is then mounted in the missile at right angles to the desired input axis. A schematic of the unit is shown in Figure 4-3.

In a typical installation, three of these units would be placed on orthogonal (mutually perpendicular) axes to measure missile attitude with respect to pitch, roll, and yaw. The three gyros are placed on a single platform and are used to keep that platform in a fixed, or inertial, orientation regardless of the motion of the missile itself. Since these gyros sense only rotational motion, another sub-system must be installed to measure translation of the center of gravity of the missile. This function is accomplished by accelerometers.

4-4 LINEAR ACCELEROMETERS

Newton's Second Law, $F = ma$ (where mass is assumed constant), is utilized to measure accelerations in a given direction. If a known mass applies a known force, then it will have a known acceleration, and this acceleration is the force divided by the mass. In its simplest form an accelerometer may be composed of a mass which is free to move in one direction against the action of a spring. If the mass is $m \frac{\text{lb-sec}^2}{\text{ft}}$, and the spring constant is $K \frac{\text{lb}}{\text{ft}}$, the acceleration is

$$a_x = \frac{KX}{m} \frac{\text{ft}}{\text{sec}^2} \qquad (4-4)$$

where X is the distance in feet that the spring is compressed or stretched. Therefore, the acceleration in the X direction is directly proportional to the distance X. Thus, three orthogonal accelerometers will measure accelerations along the three axes of a coordinate system.

A more sophisticated component is the integrating gyroscopic accelerometer shown in Figure 4-4. This device closely resembles the gyro shown in Figure 4-3, with the exception of a pendulous mass mounted on one end of the rotor spin axis. An acceleration, a_i, along the input axis causes this mass to exert a torque on the gyro about the output axis, which attempts to rotate the spin axis through an angle θ_0. The voltage induced in the signal generator is used to drive a servo motor mounted on the input axis which applies a torque, producing a precession which opposes the acceleration torque, thereby keeping the spin axis at its null position. If the spin axis should be allowed to rotate more
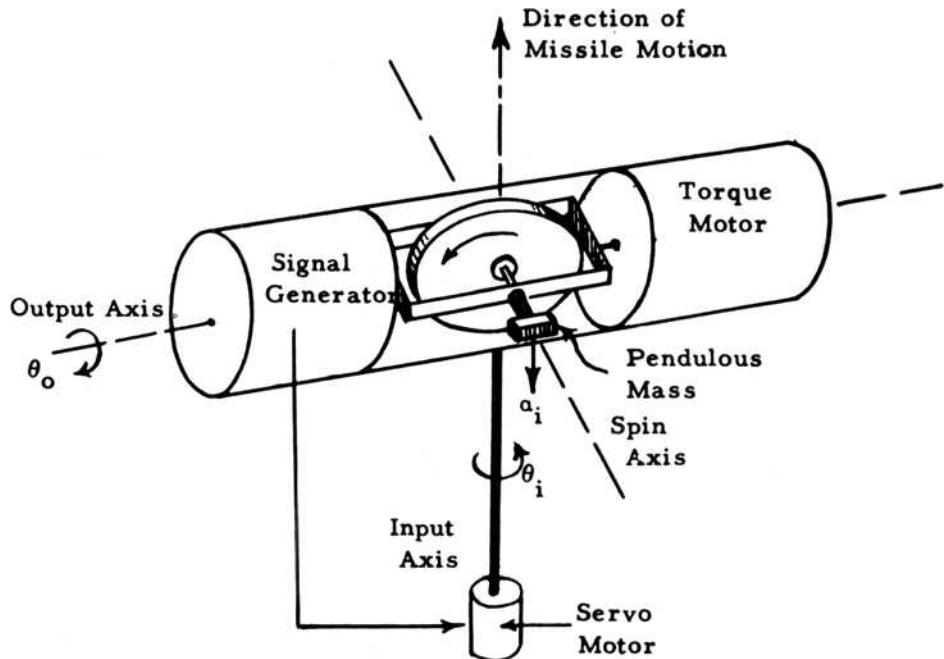
Fig. 4-4 Integrating gyroscopic accelerometer.

than a few degrees, the pendulous mass would pick up accelerations at right angles to the desired axis, introducing errors of considerable magnitude.

The torque of the servo motor is $h \dfrac{d\theta_i}{dt}$, and the torque of the pendulous mass is mla_i, where,

$h =$ angular momentum of the entire cylindrical case about the input axis

$\dfrac{d\theta_i}{dt} =$ angular velocity of case about the input axis

$m =$ mass of the pendulous mass

$l =$ moment arm of pendulous mass from gyro center

$a_i =$ acceleration along the input axis

Since the two torques are balanced,

$$h = \frac{d\theta_i}{dt} = mla_i \qquad (4\text{-}5)$$

$$d\theta_i = \frac{ml}{h} a_i dt \qquad (4\text{-}6)$$

$$\theta_i = \frac{ml}{h} \int a_i dt = \frac{ml}{h} V_i \qquad (4\text{-}7)$$

where V_i is the velocity along the input axis.

From (4-5) it is seen that the angular velocity of the servo motor is proportional to acceleration, while from (4-7) it is seen that the angular position of the servo is proportional to velocity. It is essential that the gyro assembly maintain a fixed orientation in space so that only the acceleration along the input axis will be sensed. Once more three identical units will be needed for the three coordinate axes, to measure accelerations in the X, Y, and Z directions. Later the important role played by the torque motor shown on the output axis of Figure 4-4 will be discussed.

In order to provide an inertial orientation in space for the three accelerometers, a platform stabilized by integrating gyros is commonly used. The accelerometers are mounted on the

platform along mutually perpendicular axes, and the entire platform is suspended in a series of gimbals, giving it complete freedom from missile rotation.

4-5 STABLE PLATFORM

The stable table used in inertial navigation should ideally maintain a fixed orientation in space. If, however, there is any friction present in the gimbal bearings, a certain amount of table tilt will be introduced. It is the function of the integrating gyros on the platform to sense this angular change by the method previously outlined and to correct the tilt by applying a voltage to small motors mounted on the gimbal axes. The gimbal motors, then, counter-balance any gimbal bearing friction, keeping the table stable. Now that an inertial reference plane is available, accelerations with respect to that plane may be measured. In order to use the accelerations, though, the direction in which the stable table is stabilized must be known. Furthermore, the acceleration of gravity must not be confused with a true acceleration of the missile.

The initial proper orientation of the table is a part of missile calibration during count-down. First, a guidance plane is chosen, being defined by the launch point, the target, and the center of the earth. The trajectory is then in the same plane as a great circle through the launch point and target. Before launching, the table is set perpendicular to a line through the center of the earth. Next, the longitudinal and lateral accelerometers are positioned along and perpendicular to the tangent to the earth along the trajectory. The components of the earth's gravitational acceleration and centrifugal acceleration must be continuously subtracted from the readings of the accelerometers in order to provide true acceleration and, by integration, velocity and range. The success of the mission will be completely dependent on the lack of such errors as gyro drift, table tilt, and computer inaccuracy.

4-6 GUIDANCE COMPUTER

The function of the computer is to correct continuously for predictable errors and to calculate the position and velocity of the missile. The computer corrects errors in position by commanding missile maneuvers through a servo control system. Errors in velocity are reduced by varying the throttle setting or by adjusting the motor burn-out time. Predicable errors are those associated with gyro drift, gimbal friction, variations in the gravitational field, Coriolis acceleration, and oblateness of the earth.

For trajectories which cover more than a small fraction of a great circle, increased accuracy is obtained by keeping the stable table perpendicular to the earth at all times. This feat is accomplished by causing the platform to precess at a rate equal to the angular rate of the missile about the earth's center. Both the range and the lateral accelerometers will then be able to measure missile accelerations without the added burden of a large bias acceleration due to gravity. The amount of precession necessary is calculated by the computer and applied to the three integrating gyros on the platform. When the missile reaches the target the measured vertical will coincide with the programmed vertical at that point and the computer will know the trajectory has been completed.
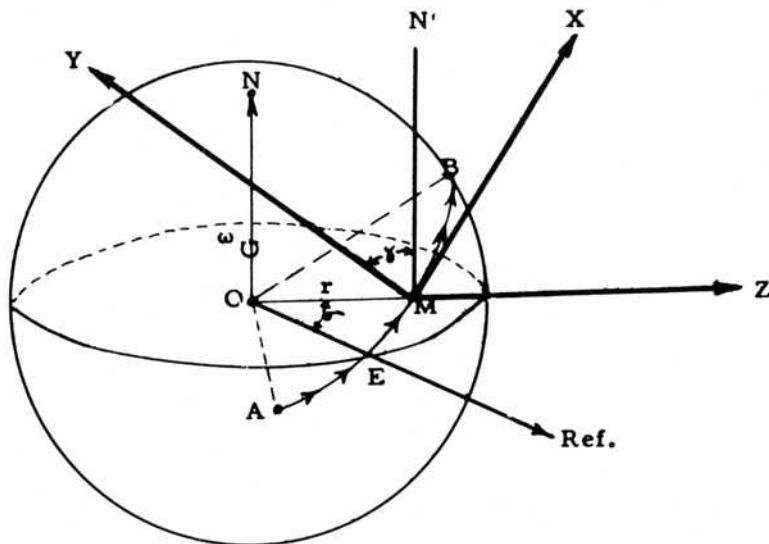
Fig. 4-5 Inertial guidance plane.

In Figure 4-5, the following items are depicted:

A: launch point
B: target
O: center of earth
M: position of missile
E: intersection of trajectory and equator
ON: polar axis
MN': reference line parallel to ON
AOB: the guidance plane
AMB: the great circle path of the missile
X: axis tangent to trajectory in AOB plane
Y: horizontal axis perpendicular to trajectory
Z: vertical axis through center of earth in AOB plane
ω: rotational velocity of earth $\left(\dfrac{\text{rad}}{\text{sec}}\right)$
r: radius of missile (OM) from center of earth

From the figure, the angular rates of precession required to maintain a vertical plumb on the stable platform may be determined. The necessary rates about the X, Y, and Z axes are:

$$\omega_x = \omega \sin\gamma \cos\sigma$$

$$\omega_y = \omega \cos\gamma + \dot{\sigma}$$

$$\omega_z = \omega \sin\gamma \sin\sigma \qquad (4\text{-}8)$$

where again the dot notation ($\dot{\sigma}$) has been used to indicate a time derivative.

Equations (4-9), (4-10), and (4-11) are the guidance equations which the computer must continuously solve. The derivation of the equations is beyond the scope of the text. They are included only to indicate the complexity of the acceleration calculations and to show the number of corrections necessary to allow for a non-spherical, rotating earth. The quantities Ax, Ay, and Az are the accelerations actually measured by the accelerometers along their respective axes. The quantities $\ddot{X}$, $\ddot{Y}$, and $\ddot{Z}$ are the true missile accelerations with respect to the earth, and e is the ellipticity factor of the earth $\left\{\dfrac{1}{231}\right\}$.

$$\ddot{X} = \frac{1}{r}[Ax - 2\dot{r}\,\dot{\sigma} - 2\omega r \cos\gamma + 2\omega y \sin\gamma \sin\sigma + 2eg \sin^2\gamma \sin^2\sigma] \qquad (4\text{-}9)$$

$$\ddot{Y} = Ay + 2\omega \dot{r} \sin\gamma \cos\sigma - 2\omega r \,\dot{\sigma} \sin\gamma \sin\sigma$$
$$- g\frac{y}{r} + 2eg \sin^2\gamma \sin\sigma \qquad (4\text{-}10)$$

$$\ddot{Z} = Az + g + r\,(\dot{\sigma})^2 + 2\omega r\,\dot{\sigma} \cos\gamma$$
$$- 2\omega \dot{y} \sin\gamma \cos\sigma \qquad (4\text{-}11)$$

Integration of (4-9), (4-10), and (4-11) will produce velocity and distance travelled at any time in each of the three directions.

4-7 SCHULER PERIOD

One of the most outstanding features of all inertial navigation systems is the inherent Schuler oscillation, discovered in 1923. Schuler (a German) correctly predicted that any inertial system will cause an undamped sinusoidal oscillation with a period of 84 minutes, if an error in position is introduced. For example, if the assumed location of the launch point is in error by one mile, the missile will, during flight, wander back and forth across its desired trajectory with an 84 minute period, but always remaining within one mile of the trajectory.

Figure 4-6 is an exaggerated diagram showing an error in position of an inertial stable table. Assuming σ is a small angle, such that $\sin\sigma \simeq \sigma$, the acceleration of the table toward its desired position is described by (4-12), (4-13), and (4-14).

$$R\ddot{\sigma} = -g\,\sigma \qquad (4\text{-}12)$$

$$R\ddot{\sigma} + g\,\sigma = 0 \qquad (4\text{-}13)$$

$$\ddot{\sigma} + \frac{g}{R}\sigma = 0 \qquad (4\text{-}14)$$

The solution of (4-14) is an undamped sine wave with a frequency of $\omega_n = \sqrt{\dfrac{g}{R}}$, or a period of $T = 2\pi\sqrt{\dfrac{R}{g}} = 84$ minutes. Obviously, the Schuler period will increase as distance from the earth increases. As locations on the earth's surface become more accurately known, and as guidance components become more precise, the errors in long range inertial navigation will be greatly reduced.
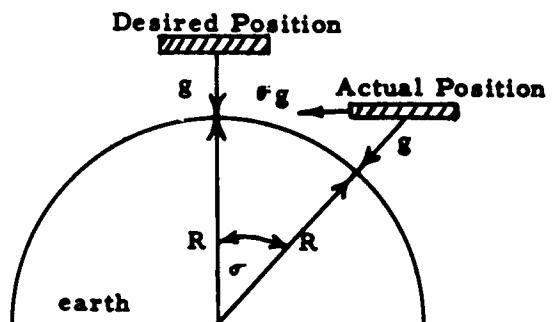
Fig. 4-6 Eighty-four minute period.

4-8 SUMMARY

Pure inertial guidance is ideally suited to long range, high speed navigation. For a long time of flight, however, some method of correcting errors due to gyro drift is highly desirable. One such method is celestial navigation coupled to inertial navigation, which provides periodic accurate fixes over the earth's surface as a means of checking the missile's position. Another technique recently developed is automatic radar map-matching, in which a radar view of the terrain below the missile is electronically compared with a previously prepared radar map of the same area.

Many of the components described in this
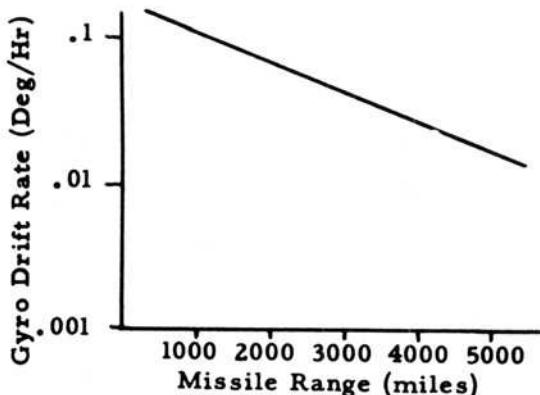
Fig. 4-7 Gyro drift rate per 1000 ft of miss distance.
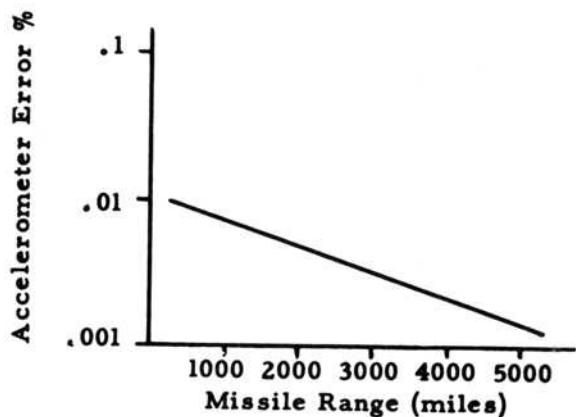
Fig. 4-8 Accelerometer % error per 1000 ft of miss distance.

chapter are currently being used in missiles which are not inertially guided. For example, air-to-air and surface-to-air short range missiles may utilize integrating gyros for attitude control, and eacc lerometers for velocity control. Guidance computers are used, but are often left on the ground, or in the launching aircraft.

An appreciation of the accuracy necessary for current inertial components may be gained from the realization that an error of as much as one foot per second in burn-out velocity or .05 degrees in burn-out pitch attitude will cause an intercontinental ballistic missile to miss the target by about one mile. Accuracy requirements are summarized in Figure 4-7 for gyros and in Figure 4-8 for accelerometers.

REFERENCES

1 A. S. Locke, *Guidance—Principles of Guided Missile Design*, Princeton, N. J., D. Van Nostrand Co., Inc., 1955.

2 *Air University Quarterly Review*, Vol. IX, No. 3, Maxwell AFB, Ala., Summer 1957, p. 34.

3 *Jet Propulsion*, Vol. 28, No. 1, New York: American Rocket Society, January 1958, p. 17.

4 *Jet Propulsion*, Vol. 28, No. 2, New York: American Rocket Society, February 1958, p. 111.

5 *Missiles and Rockets*, Vol. 3, No. 2, Washington, D.C., American Aviation Publications, Inc., February 1958.

CHAPTER 5

GUN TUBES

5-1 HISTORICAL SUMMARY OF DEVICES FOR LAUNCHING PROJECTILES

In the pre-gunpowder period, man tried to increase the range of his weapons by using various types of catapults and ballista. These methods of projectile propulsion were nothing more than great slings used to hurl stones and other large, heavy objects for a considerable distance.

The invention of gunpowder about 1250 A.D., brought into use the first smooth-bore cannon. These cannon fired rounds of stones or darts of iron. They were often laid on the ground or with the muzzle end raised up by a mound of dirt or a block of wood. One of the earliest recorded uses of firearms in warfare is that of an attack on Seville, Spain, in 1247. History also records that cannon were used by King Edward III of England at Crecy in 1346, and by Mohammed II of Turkey in his famous conquest of Constantinople in 1453.

The first firearms were large, heavy, and inefficient, and were not capable of being carried by an individual soldier; hence the development of cannon preceded that of small arms by about 50 years. The tube of a gun was then made like a barrel, of wooden staves bound together with hoops of iron; in the English language it has ever since been named a barrel.

The late smooth-bore period showed the gradual improvement of smooth-bore weapons, iron and bronze being used for cast tubes; and some of the first attempts to attain mobility by placing the smooth-bore cannon on various types of carriages. During this period artillery began to be recognized as an arm independent of infantry and cavalry.

A period of transition followed (about 1845 to 1885), during which breech loading, rifling, and fragmentation projectiles were tried and accepted. Distinction began to take place between guns, howitzers, and mortars. The first crude recoil mechanisms appeared, and smokeless powder was invented.

The latest or modern period, continuing up to the present time, has resulted in the development of artillery as we find it today, firing high velocity ammunition, breech-loaded, from improved steel guns on mobile mounts embodying mechanisms to absorb the recoil.

Rocket propelled weapons have been used in warfare as long as gunpowder has been available. Previous to World War II, however, their effectiveness was limited because of their extreme lack of accuracy. With the advent of improved propellants and launching techniques during World War II, rockets became an important element of the artillery arsenal. Since that time, development of guidance techniques and of rocket engines capable of propelling missiles at extreme velocities over very long ranges, have made rocket and jet propelled guided missiles at least of equal importance to gun propelled artillery.

In the case of conventional artillery, the launching vehicle is the gun. Rockets and guided missiles are launched using devices known simply as launchers. The design of both guns and launchers entails careful study of all system variables in order that the projectile or missile will be properly launched on its prescribed trajectory.

Guns are discussed in this text in several chapters: Chapter 5 presents a general discussion of tubes and associated components; in Chapter 6, stresses in gun tubes are studied; Chapter 7 contains description and analysis of recoil systems; Chapter 8 discusses mounts and launchers, including stress analysis; Appendix A gives a description of methods of manufacture of gun tubes. Descriptive data concerning guns is limited in this text because space is not available for detained description. For the reader interested in the description and operation of weapons and components, Department of Army Technical Manual 9-2305, *Fundamentals of Artillery Weapons,* is recommended. Missile launchers are briefly discussed in Chapter 8.
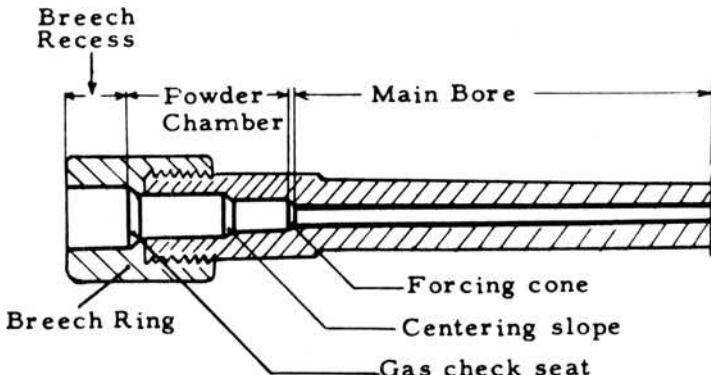
Fig. 5-1 Components of a barrel assembly.

5-2 GUNS—DEFINITIONS

In Figure 5-1 various parts of a gun are indicated. These include the following:

(a) Barrel assembly: consists of tube, breech ring, and in some cases hoops, jackets, and liners.

(b) Tube: that part of the barrel assembly which contains the rifled bore and the chamber for the ammunition.

(c) Breech ring: that part of the barrel assembly which houses the breech mechanism.

(d) Breech recess: that space at the rear of the barrel assembly formed in the interior of the breech ring to receive the breechblock.

(e) Chamber: that part of the tube extending from the rear face of the tube to the forcing cone.

(f) Gas check seat: that portion of the rear interior of the tube (in guns firing separate-loading ammunition) which is tapered to receive the gas check pad of the breech mechanism to insure proper obturation when firing. In guns firing fixed or semi-fixed ammunition, obturation is performed by expansion of the cartridge case against the walls of the powder chamber, so that the tapered gas check seat is eliminated.

(g) Centering slope: tapered portion at or near the forward end of the chamber which causes the projectile, during the loading operation, to center itself in the bore.

(h) Forcing cone: interior tapered portion of the tube between the chamber and the bore, including the tapered origin of the lands. It allows the rotating band of the projectile to be engaged gradually by the rifling and aids in centering the projectile within the bore.

(i) Bore: the cylindrical rifled portion of the tube interior extending from the forcing cone

to the muzzle.

(j) Rifling: a number of helical grooves cut in the bore of a gun, beginning at the forcing cone and extending to the muzzle (Figure 5-2). The surfaces of the bore between the grooves are called the lands.

(k) Caliber: the caliber of an artillery piece is the diameter of the bore, not including the depth of the rifling (Figure 5-2).

The term caliber is also used as a unit to express the length of a weapon, measured from the face of the breechblock to the muzzle. A unit of one caliber in length is equal to the diameter of the bore between lands. Artillery weapons are divided into types (Figure 5-3) which have characteristic lengths as follows:

Mortar: 10 to 20 calibers

A mortar has a smooth bore, usually, and a low muzzle velocity. Fired at high elevation it can reach nearby targets that are concealed by intervening hills or other barriers.

Howitzer: 20 to 30 calibers

A howitzer, intermediate between the gun and the mortar, has a medium muzzle velocity and delivers high angle fire to reach targets hidden from flat trajectory guns.

Gun: 30 to 50 calibers or more

As compared with a howitzer, a gun has a longer barrel, higher muzzle velocity, flat trajectory, and a more limited maximum elevation (except antiaircraft guns). It is used for long-range fire or for the delivery of fire requiring a flat trajectory and high velocity.

Recoilless weapons, regardless of the number of calibers of length, are called recoilless rifles.
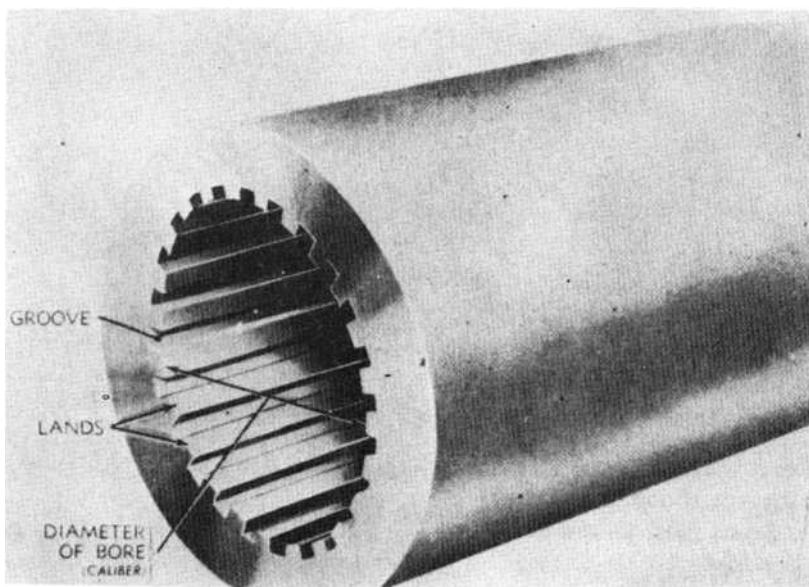
Fig. 5-2   Measurement of caliber.

Fig. 5-3   Types of artillery weapons.

5-3   BREECH MECHANISMS—GENERAL

In the era of the muzzle loading cannon, the cannon had to be depressed for loading, the loader was in danger, and the rate of fire was limited. Since that time the continual development in breech mechanisms has produced the safety, high rate of fire, and convenience which are taken for granted in the modern weapon.

A satisfactory breech mechanism must be easy and quick to operate. If it is operated manually, its operation must be quick enough that it does not delay the rate of fire, and easy enough that the operator will not become unduly fatigued during continuous firing. With automatic or semi-automatic weapons, the mechanism must be adapted to operation by a cam and lever arrangement.

Safety is another very important requirement. For a gun crew to operate most efficiently, the men must have confidence that they will not be injured in serving the weapon.

The obturation must be complete Obturation is the sealing of the propellent gases in the chamber, both to the front and to the rear.

5-4   BREECHBLOCKS

The breechblock is the principal part of the breech mechanism and is essentially a large heavy piece which positively closes or covers the back end of the barrel. The two general types of breechblocks are: interrupted-screw type and sliding-wedge type.
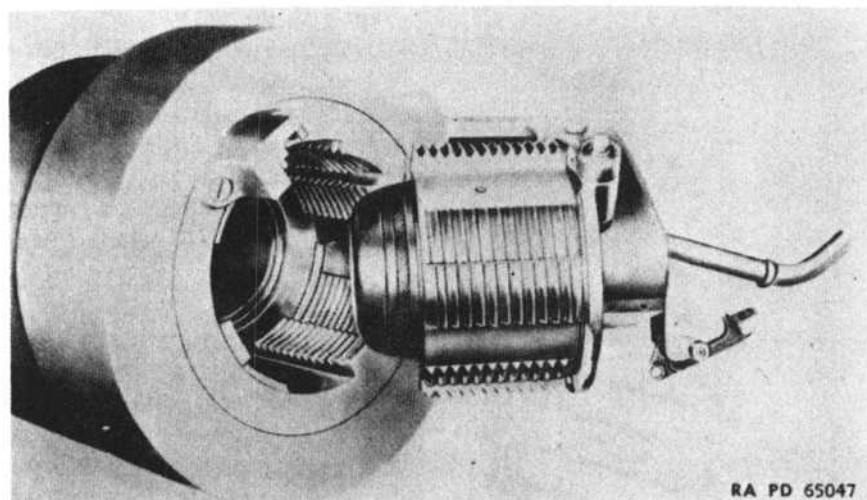
Fig. 5-4 Welin breechblock.
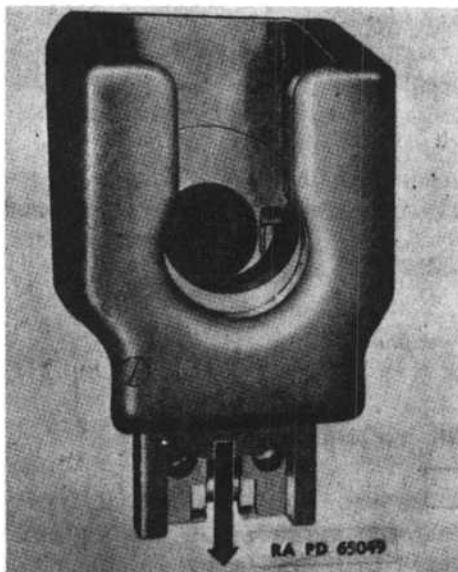
Fig. 5-5 Vertical sliding-wedge breechblock.
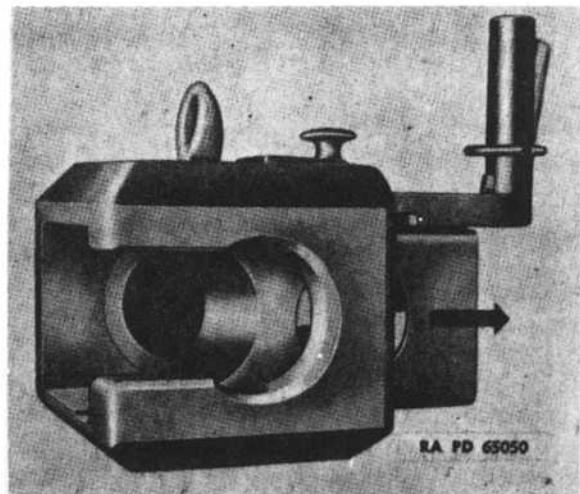
Fig. 5-6 Horizontal sliding-wedge breechblock.

5-4.1 INTERRUPTED-SCREW

The most common type of interrupted-screw breechblock is the stepped thread (Welin) breechblock. The breech recess and the breechblock are cut with a series of stepped threads (Figure 5-4) so that when the breechblock is inserted and turned in the breech recess, matching sections of stepped threads engage. Using the stepped type of thread, a large threaded surface or holding area is possible. This breechblock is used on modern cannons which fire separate loading ammunition because of the ease of adapting an obturating device to the assembly.

5-4.2 SLIDING-WEDGE

The sliding-wedge breechblock is rectangular in cross section and slides in a rectangular recess in the breech ring. Where the motion of the breechblock is vertical, the mechanism is referred to as the vertical sliding-wedge (Figure 5-5). When the motion is horizontal, the block is called a horizontal sliding-wedge breechblock (Figure 5-6).
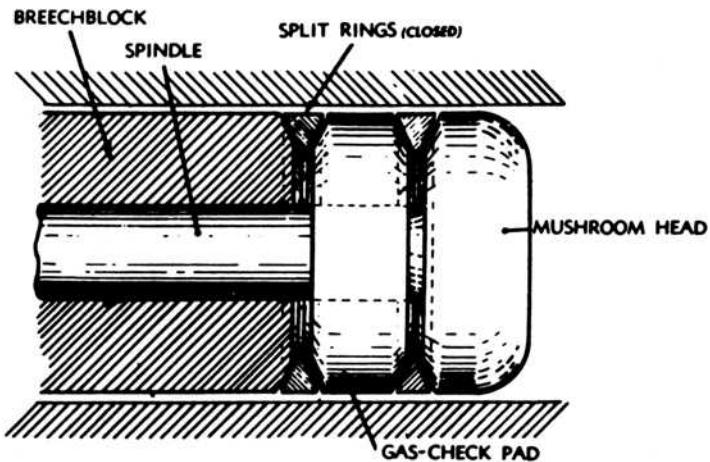
Fig. 5-7 DeBange obturator.

5-5 OBTURATION

Obturation is the sealing of the propellent gases in the chamber both to the front and to the rear. The rotating band, in the case of artillery projectiles, and the gilding metal jacket, in the case of small arms bullets, provide forward obturation. When considering breech mechanisms we are concerned with the prevention of the rearward passage of powder gases into the threads and other parts of the breech mechanism. These gases, which have great velocities and high temperatures, would soon erode and ruin the breech mechanisms and would materially affect the ballistics of the weapon if a means of obturation were not introduced. In weapons using fixed or semifixed ammunition, obturation is performed by the cartridge case, which expands under pressure from powder gases in the bore to form a tight seal against the walls of the powder chamber. In weapons using separate loading ammunition, an obturating device must be included in the breech mechanism to prevent the rearward escape of powder gases. The DeBange obturator is used exclusively in American weapons.

The DeBange obturator is illustrated schematically in Figure 5-7. The mushroom head of the obturator is formed integrally with a spindle which passes through the breechblock. The spindle and mushroom head are free to move

back and forth. Between the mushroom head and the breechblock is a pad made of asbestos and non-fluid oil, or, in some cases, made of neoprene rubber. This pad is called the gas check pad. Two split steel rings, which are ground accurately to bear against the walls of the bore, encircle the gas check pad. The spindle and mushroom head have a small hole drilled axially to allow the flame from the primer to go through the breechblock and reach the propelling charge. When the weapon is fired, the gas pressure acts against the mushroom head, moving it back and compressing the pad. This causes the pad to expand radially against the split rings, which in turn expand to make a gas tight seal against the bore wall. After firing, the gas pressure is dissipated; the pad returns to its normal shape, moving the mushroom head forward; the split rings contract to their original size; and the breechblock is then free to open. The gas check pad, split rings, and mushroom head do not rotate with the breechblock during the closing or opening, but the breechblock proper rotates about the spindle mushroom head assembly as an axle. In actual practice, there is always a small split ring around the spindle to prevent the escape of gas at this point, and a filling-in disk which forms a bearing between the pad and rotating block.
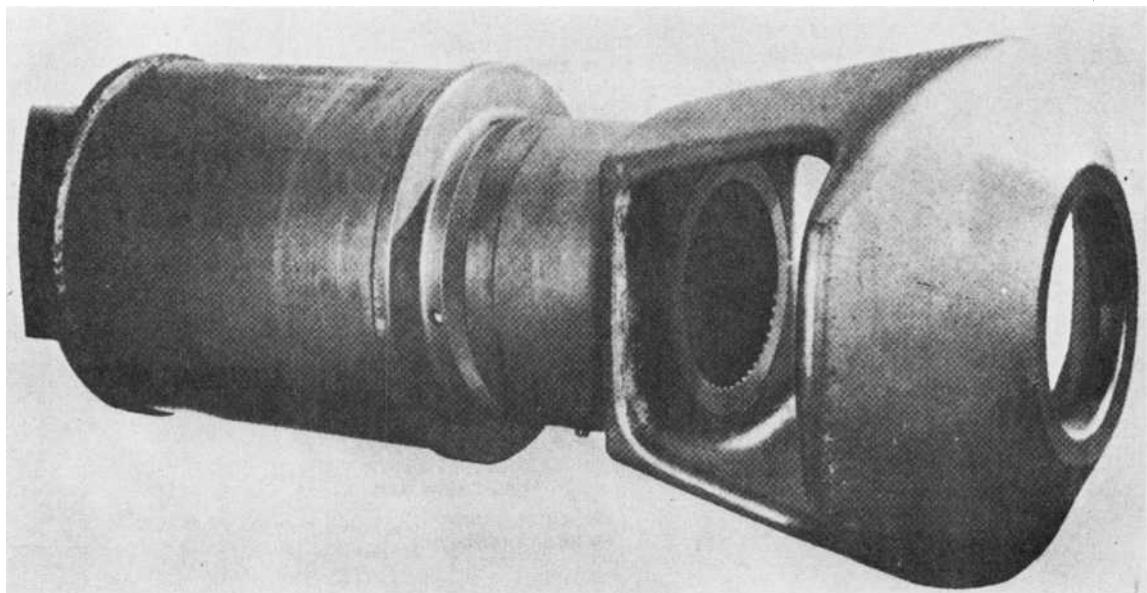
Fig. 5-8   Bore evacuator and muzzle brake.
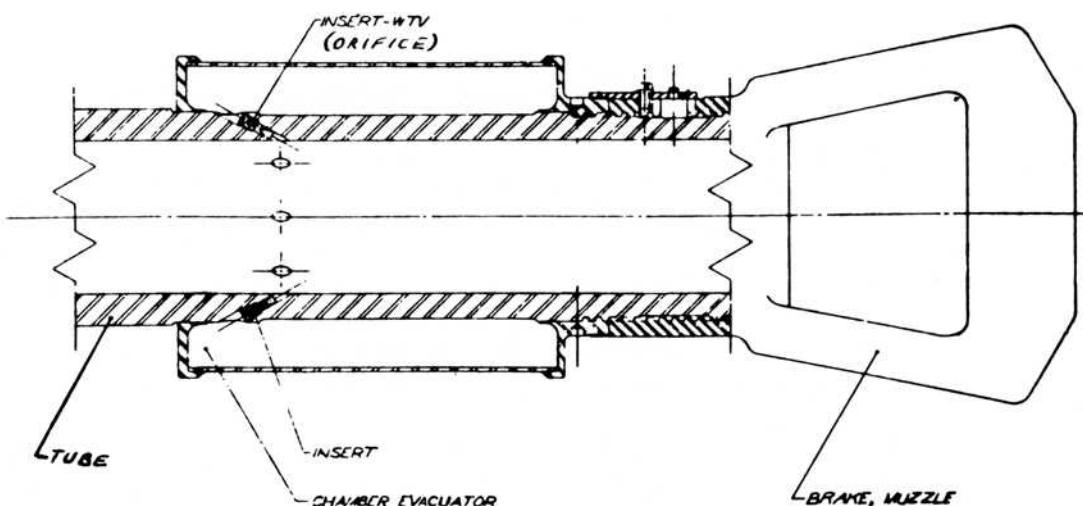
Fig. 5-9   Cross section of bore evacuator.

5-6   BORE EVACUATORS

Gas ejector systems, also known as air scavenger systems, have been used for many years on large caliber seacoast and naval weapons to clear gases and residue out of the barrel after firing. The system involves pipes and valves which allow the injection of compressed air through the breech into the powder chamber after each round.

A more recent method employs a bore evacuator (Figure 5-8), which is a metal jacket attached near the muzzle, accessible to bore gases through inclined orifices in the tube. Its action is simple and entirely automatic. Some of the powder gases following behind the projectile flow through the small orifices in the tube (Figure 5-9) into the evacuator chamber after the

projectile has passed the orifices. Pressure is thus built up in the evacuator chamber and is maintained until that in the tube drops. The gases then flow back into the tube in the direction of the muzzle and create a partial vacuum which, as the breech opens, clears the bore.

5-7 SAFETY DEVICES

Artillery weapons are equipped with necessary safety devices to protect personnel and material. As needed, a given weapon may contain devices which prevent:

(a) Premature discharge.

(b) Powder gases from escaping from the powder chamber to the rear.

(c) The breechblock from opening or rotating when the weapon is fired.

(d) High angle weapons from firing at too low an angle and endangering the emplacement or friendly personnel.

(e) Firing when the cannon is disconnected from the recoil system.

(f) Operation of the firing mechanism when the breechblock is not fully closed.

(g) Firing when the cannon is not in battery.

(h) Firing with excessive head space present.

(i) Firing into friendly territory.

(j) Accidental elevating or traversing while traveling.

The breech mechanisms and firing mechanisms are so designed, equipped and assembled that they will prevent premature discharge, rearward escape of powder gases, and unseating of the breechblock. Prevention of premature discharge is accomplished by preventing use of the firing mechanism, or assembly of it to the breechblock, before the breech is fully closed Mechanical devices such as cam operated, spring actuated locks and plungers function between the breechblock mechanism and firing mechanism to make up this safety device. On weapons that are fired electrically, the electric firing circuit is broken by means of circuit breakers or switches, and firing is rendered impossible until all precautionary measures and operations have been carried out.

Positive stops and locks are provided on weapons if it is necesary to prevent accidental firing at too low or too high an elevation, or into friendly territory. Similar stops and locks are used on all mobile weapons or tank armament in order to prevent damage to weapon, undue wear of gear trains due to road shocks, or injury to personnel by accidental and uncontrolled traversing or elevating during traveling.

5-8 THEORY OF RIFLING

The term rifling was defined in Par. 5-2. The purpose of rifling is to impart to elongated projectiles the rotation necessary to insure stability in flight. The projectile is constructed with one or more rotating bands of soft metal, slightly larger in diameter than the bore of the gun. As the projectile moves down the bore under the action of the propellent gases, the lands cut through the rotating band, engraving it to conform to the cross section of the bore, and causing rotation of the projectile.* The ribs of metal from the band projecting into the grooves prevent the escape of gas past the projectile. This function of the band is called forward obturation.

The twist of rifling at any point is the inclination of a groove to the element of the bore through the point. It may be uniform, increasing, or a combination of the two. It is usually expressed in terms of the number of calibers of length in which the groove completes one complete turn, for example, one turn in 40 calibers. In uniform twist, the degree of twist is constant from the origin of rifling to the muzzle, the path of the groove being a helix. In increasing twist, the degree of twist increases from zero or some small value, for example, one turn in 50 calibers at the origin, to a sharper twist at the muzzle, such as one turn in 25 calibers. The rate of increase may be uniform or become more rapid.

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* In recoilless weapon systems the rotating band is pre-engraved, so that the lands do not perform the engraving function. This reduces stresses in the gun tube and allows a thinner tube wall. It also reduces the energy lost in the engraving process, so that more of the propellant's energy content can be converted into kinetic energy of the projectile.
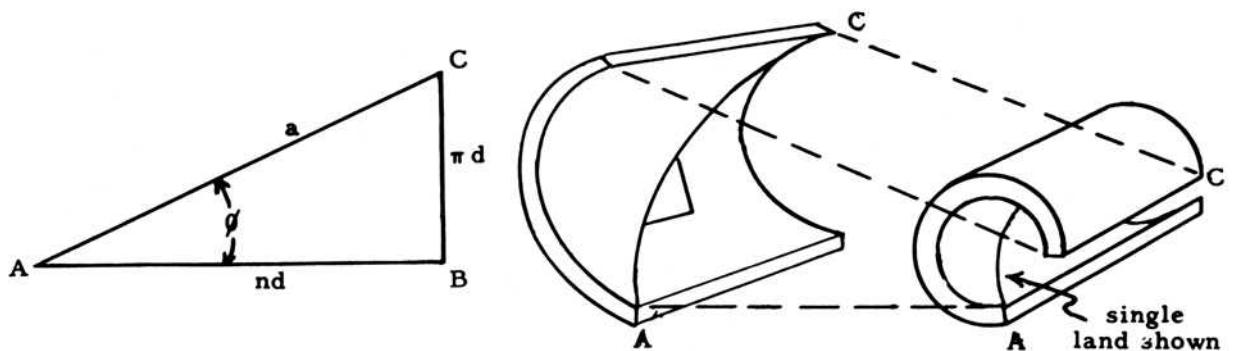
Fig. 5-10 Developed curve of rifling.

Certain designers have employed the increasing twist to a point several calibers from the muzzle and uniform twist from there on. Rifling is specified by the developed curve of the groove. For uniform twist, the developed curve is a straight line as indicated by *AC* in Figure 5-10. In increasing twist, the form of the curve is usually parabolic.

To consider in more detail the case of uniform twist rifling,

let ϕ = angle of twist
n = number of calibers of length in which a groove completes one turn
d = diameter of bore, ft

Then for the value of the tangent of the angle of twist

$$\tan \phi = \frac{\pi d}{nd} = \frac{\pi}{n} \qquad (5\text{-}1)$$

For rifling with increasing twist ϕ is variable, but the value of its tangent at any point is $\frac{\pi}{n}$.

To establish the relation between the velocity of translation and the velocity of rotation of the projectile,

let v = velocity of translation of the projectile at any point of the bore, ft/sec
ϕ = angle of twist of the rifling at the same point
ω = angular velocity of the projectile at the same point, rad/sec
d = diameter of the bore, ft

Then the linear velocity of rotation of a point on the outside surface of the projectile is evidently $v \tan \phi$.

The angular velocity is therefore

$$\omega = \frac{2v \tan \phi}{d} \qquad (5\text{-}2)$$

Knowing the muzzle velocity and the twist at the muzzle, the velocity of rotation of the projectile as it leaves the gun may be determined.

Standard rifling design practice is based upon theoretical computations of forces and stresses, experimental tests, data from service firings, and practical manufacturing considerations. Influencing factors include the following:

(a) Ballistics. The system of rifling and the angle of twist selected depend both upon the gun and the projectile and must be such that with the established muzzle velocity the necessary rotation will be imparted to a projectile of a given design to insure stability in flight. The type of fuze used may dictate the maximum velocity of rotation permitted.

(b) Strength. The number, width, and profile of the lands must be such as to withstand the stresses set up as the projectile passes through the bore. The type and twist of rifling should develop stresses on both gun and projectile which are within allowable limits.

(c) Wear. The accuracy life of a weapon depends primarily on the condition of the rifling. The degree of wear is affected by the type and twist employed, and by the width, number, depth, and form of the lands and grooves. In one instance the accuracy life of a gun of a certain design was doubled by decreasing the degree of uniform twist, increasing the width of lands and depth of grooves, and decreasing the number of

lands and grooves.

The primary consideration is that the projectile should emerge from the muzzle with the proper rotational velocity. The characteristics of both the gun and the projectile are involved. Underspin will result in tumbling and instability of flight. In overspin, the longitudinal axis of the projectile will tend to retain its same position during flight, not adapting its direction to the curved line of flight, and thus not insuring head-on impact.

Both the uniform and the increasing systems of twist have their advantages and both systems have been employed. However, the uniform twist is now specified for all U.S. Army guns, except the 40-mm gun (Bofors), the 240-mm howitzer, and the 4.2-inch mortar. The 40-mm gun (Bofors), for example, has a twist increasing from one turn in 45 calibers at the breech to one turn in 30 calibers at the muzzle. Comparing the two systems, it is apparent that, to produce the same rotational velocity at the muzzle, the use of increasing twist will result in less driving force on the driving side of the land and on the rotating band, when the projectile is near the origin of rifling, and when it is at the point of maximum powder pressure and acceleration, than if uniform twist is used; at the muzzle, however, this will be reversed. However, if the rate of increase of twist is properly selected, the maximum stress on the lands and on the rotating band of the projectile will be less with increasing twist than with uniform twist. The danger of stripping the rotating band from the projectile is thus reduced by use of the increasing twist, but this advantage has been minimized by the development of modern progressive burning powders, with properly selected granulation, which permit attainment of the desired muzzle velocity with lower maximum pressures. With the uniform twist, the rotating band is engraved initially to the exact form which will be maintained throughout the length of travel in the bore and there is no subsequent displacement of band metal. With increasing twist, however, there is a continuous change in the angle of the grooves engraved in the band, with continuous displacement of metal. Initially the grooves are approximately parallel to the axis of the projectile, but,

as the twist of rifling increases, they must conform to this constantly changing angle. The resulting disadvantages of the increasing twist are: (1) concentration of driving pressure on the forward part of the band, with high pressure on the driving edge of the land; (2) increased friction, abrasion, and temperature; and (3) higher value for total passive resistance although the starting resistance is less. Rifling with increasing twist increases manufacturing costs somewhat. The apparent advantages of the uniform twist over the increasing are reflected in the present general tendency of all countries to specify the former type. There are sufficient proponents of the use of increased twist, however, to warrant further study of this type. One leading ordnance installation is at present experimenting with increasing twist of rifling for hypervelocity (i.e., greater than 3500 ft/sec) guns.

If the twist increases from zero at the breech uniformly to the muzzle, the equation of the developed curve of the rifling will be of the form

$$y = au + bu^2 \qquad (5\text{-}3)$$

where u is measured parallel to the bore and y is perpendicular to that direction. Differentiating (5-3) twice with respect to u, we have

$$\frac{d^2y}{du^2} = 2b \qquad (5\text{-}4)$$

That is, the rate of change of the tangent to the groove is constant. A twist in this form would offer less resistance than the uniform twist to the initial rotation of the projectile. But, to diminish this resistance still further, a twist that is at first less rapid than the uniformly increasing twist and later more rapid, has been adopted frequently for rifled guns. The equation of the semi-cubic parabola

$$u^{3/2} = 2py \qquad (5\text{-}5)$$

is generally adopted for the developed curve of rifling with increasing twist (Figure 5-11). The twist is assumed at breech and muzzle and the curve between these points is obtained from the above equation. The tangent to the curve at any point makes (with the axis of u) an angle whose tangent is dy/du. The value of the tangent

of the angle at any point is π/n (5-1). Therefore, differentiating (5-5),

$$\frac{dy}{du} = \tan\phi = \frac{3_u{}^{1/2}}{4p} = \frac{\pi}{n}$$

A cross section of the breech end of a cannon tube with right hand twist, showing the typical shape of rifling grooves and lands, is shown in Figure 5-12. The number, width, and depth of grooves increase with the caliber of the gun. The type and twist of rifling also influence the design. Shown below are some design characteristics with the advantages of each listed:

(a) Shallow grooves. Cause less weakening of gun tube; less resistant to engraving of rotating band.

(b) Deep grooves. Insure longer accuracy life of tube.

(c) Wide lands. Withstand stress on driving edge.

(d) Narrow lands. Less resistant to engraving of rotating band.

The driving edge of the land is the side which exerts the pressure against the rotating band causing rotation. It should be substantially straight and radial in direction in order that the force between projectile and land may be tangential to the wall of the tube. Rounding of corners facilitates manufacture and at the bottom is necessary to prevent the development of stress concentration cracks. The shape of the non-driving edge is less important, so long as the requisite strength is insured.

The rifling problems discussed above are naturally non-existent for smooth bore weapons such as mortars and rocket launchers. Such guns,
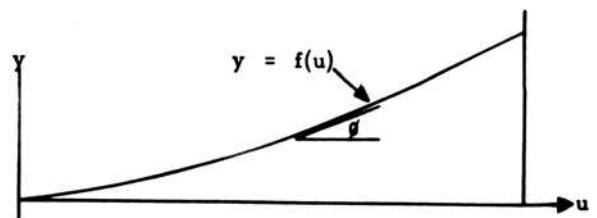
Fig. 5-11 Developed curve of rifling (using twist).
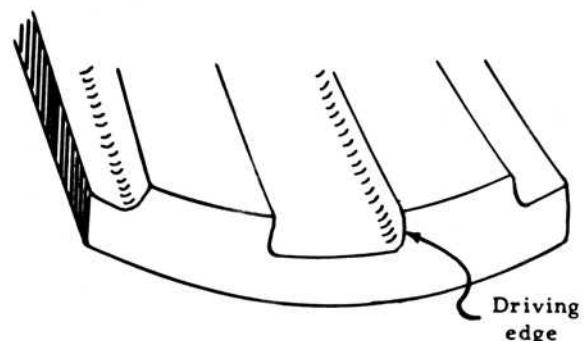
Fig. 5-12 Form of rifling (from breech end).

however, must employ fin stabilized projectiles. Experiments are being conducted on high velocity guns also, using smooth bores and fin stabilized projectiles. These combinations eliminate disadvantages of rifled guns such as high friction, abrasion, temperature, and total passive resistance to the projectile; however, the problems of gas pressure sealing and gun accuracy remain in magnified proportions. In fact, in some test weapons of this design, high erosion due to imperfect sealing of the propellent gases has resulted.

REFERENCES

1 Department of the Army Technical Manual, TM 9-2305, *Fundamentals of Artillery Weapons,* Washington, U.S. Government Printing Office, 1947.

2 Thomas J. Hayes, *Elements of Ordnance,* New York: John Wiley and Sons, Inc., 1938, pp. 153-247, 284-370.

CHAPTER 6

STRESS ANALYSIS IN CYLINDERS

6-1 GENERAL

In the design of weapon systems, each component must be carefully studied to determine the stresses to which it will be subjected. Because of the extremely high performance characteristics of modern weapons, these stresses may exceed the maximum allowable if components are improperly designed. Accelerations of the order of 20,000 or 30,000 times the acceleration due to gravity are imparted to modern artillery projectiles, causing very high stresses in the walls of these projectiles. Pressures on the order of 40,000 pounds per square inch are not uncommon in hypervelocity artillery weapons, subjecting the gun tube to extreme stresses. Long range missiles carry large weights of propellants in fuel tanks. Under even small acceleration the pressure exerted by these fuels becomes considerable.

In order that proper strength can be built into these components, still keeping weight to a minimum, the designer must analyze the stresses to which the component will be subjected and base his design (partially) upon these considerations.

Since many weapon systems components are cylindrical or nearly so, (e.g., gun tubes, projectiles, missile fuel tanks, rocket engine combustion chambers) this chapter presents a review of the stress analysis of cylindrical configurations in general, followed by specific discussions of stresses in gun tubes and artillery projectiles. Principles discussed in relation to these examples can readily be applied to other cylindrical components.

6-2 BASIC CONSIDERATIONS

When a rigid body is subjected to applied stresses in several directions at one time, the true criterion which determines failure under such complex conditions is in doubt. It will be shown later that, under such conditions, each stress modifies the strain produced by every other stress, and there may be stresses in particular directions in excess of the elastic limit, whereas the resultant strains in these directions remain less than the strain corresponding to the elastic limit. It is also possible that conditions may be such that the resultant strain is excessive, while the stress in the same direction is below the elastic limit. Hooke's law, stating that stress is proportional to strain, is applicable only for an applied load, and the corresponding strain, in one direction.

Among the number of theories which have been advanced relative to the conditions causing failure, some of the better known ones are: the maximum stress theory, which is based solely on the maximum principal stress; the maximum strain theory, which states that plastic flow will occur when the strain in any direction exceeds the strain corresponding to the elastic limit; the maximum shear theory, which is based on the greatest difference between the principal stresses; Mohr's Theory and the Von Mises-Hencky Theory, which are based on special interpretations of shearing stresses.

Any one of these theories probably could be used successfully in designing cylindrical components provided the proper interpretations were made and the safety factor adjusted accordingly. In the design of gun tubes and projectiles the Army Ordnance Corps and the Navy Bureau of Ordnance have adopted the maximum strain theory. This theory has equal application to combustion chamber walls and other components. The following basic principle will be

adopted based on this theory:

NO PART OF THE CYLINDER SHOULD BE STRAINED BEYOND THE STRAIN CORRESPONDING TO THE ELASTIC LIMIT OF THE METAL

Failure, therefore, is considered to have occurred when any part of the metal is permanently de-

formed, usually evidenced by a permanent enlargement of the diameter.

Before discussing further the component design one must develop the tools for applying this principle. More exactly, the relationships governing the magnitudes and distribution of stresses and strains in a thick-walled cylinder subjected to internal and/or external pressure must be established.

6-3 BASIC THEORY

Simple stresses. Hooke's law states that up to the elastic limit, stress is proportional to strain, or more particularly $E = \frac{s}{\epsilon}$. This basic statement relates a simple or unidirectional stress to the strain in the direction of the applied stress (see Figures 6-1 and 6-2). If against a cube of steel (modulus of elasticity, E, equal to 30×10^6 psi) one inch on a side, a stress equal to the elastic limit (100,000 psi, Figure 6-1) is applied,

the cube will elongate approximately 0.003 inches in the direction of the applied stress and measure in this direction approximately 1.003 inches. Upon release of this stress, the block will again measure 1 inch on a side. It is to be noted, however, that to obtain this elongation in the direction of the applied stress, there existed along the y and z axis a decrease in dimensions (Figure 6-2).

6-3.1 POISSON'S RATIO (μ)

Poisson, upon investigating the relationship of stress and strain in various materials, determined that an applied stress in one direction caused not only a strain in that direction but also strains in the perpendicular directions and that these strains were proportional. The specific ratio for

steel has been determined to be approximately $\frac{1}{3}$. From this relationship it may be seen (Figure 6-2) that the strain along the y and z axis will then measure $\frac{100,000}{3E}$ and will be a decrease in length of either of these sides making them then approximately 0.999 inches long.
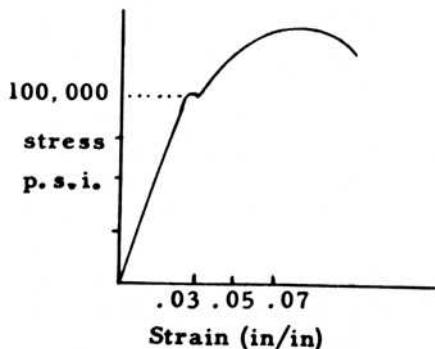
Fig. 6-1 Stress-strain diagram (mild steel).
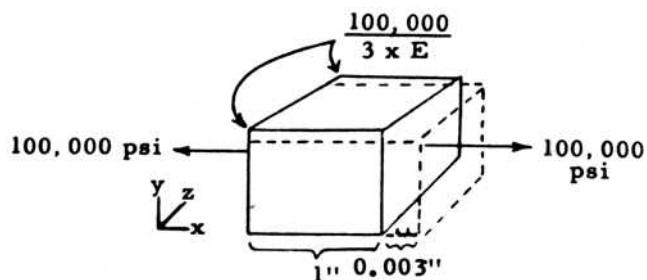
Fig. 6-2 Cube of gun steel, one inch on a side.
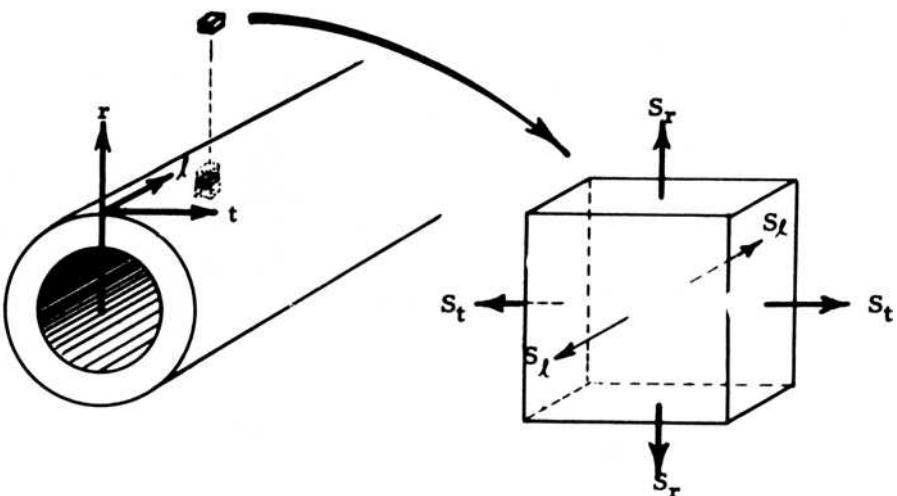
Fig. 6-3 Stress convention.

6-3.2 EQUIVALENT UNIDIRECTIONAL STRESS

The total strain to which most engineering materials are subjected does not result, however, from a single stress applied in but one direction, but is normally a strain resulting from simple simultaneous stresses of varying magnitude and sense which may be applied as resultants along the three coordinate axis system. To better visualize this, consider the cube of Figure 6-3, with the arrows indicating the positive direction of S_r (radial), S_t (tangential) and S_l (longitudinal) stresses. In the condition of simple stresses (Figure 6-2), it was seen that a stress along one axis, t, resulted in a unit elongation in that direction as well as a proportional decrease in dimensions in accordance with Poisson's ratio in the r and l directions. In the condition of stresses applied simultaneously in all of the three coordinate directions, however, a resultant strain in a degree varying from that realized by a single stress will result.

Assuming that stresses are applied in the r, t, and l directions and in a positive sense as indicated by the arrows, the resultant total strain,

ϵ_t, which would result in the tangential direction is then represented by (6-1).

$$\epsilon_t = \frac{1}{E} [s_t - \mu s_r - \mu s_l] \qquad (6\text{-}1)$$

Using a similar analysis, (6-2) and (6-3) may be determined for the resultant strains in the radial and longitudinal directions:

$$\epsilon_r = \frac{1}{E} [s_r - \mu s_l - \mu s_t] \qquad (6\text{-}2)$$

$$\epsilon_l = \frac{1}{E} [s_l - \mu s_r - \mu s_t] \qquad (6\text{-}3)$$

The fictitious tensile stress which, acting alone in the t direction, would produce the strain ϵ_t is $\Sigma_t = E\epsilon_t$. Similarly, $\Sigma_r = E\epsilon_r$ and $\Sigma_l = E\epsilon_l$ are stresses which, if acting alone, would produce the strains ϵ_r and ϵ_l. These fictitious stresses are called equivalent unidirectional stresses. The equivalent unidirectional stresses are:

$$\Sigma_t = E\epsilon_t = [s_t - \mu s_r - \mu s_l] \qquad (6\text{-}4)$$
$$\Sigma_r = E\epsilon_r = [s_r - \mu s_l - \mu s_t] \qquad (6\text{-}5)$$
$$\Sigma_l = E\epsilon_l = [s_l - \mu s_r - \mu s_t] \qquad (6\text{-}6)$$

With these basic principles in mind the stresses in the walls of cylinders can now be determined.

6-4 STRESSES DUE TO INTERNAL OR EXTERNAL PRESSURES

The major military application of thick walled cylinders is in artillery gun tubes. Therefore, the discussion of thick walled cylinders will be directed toward the solution of the problem for
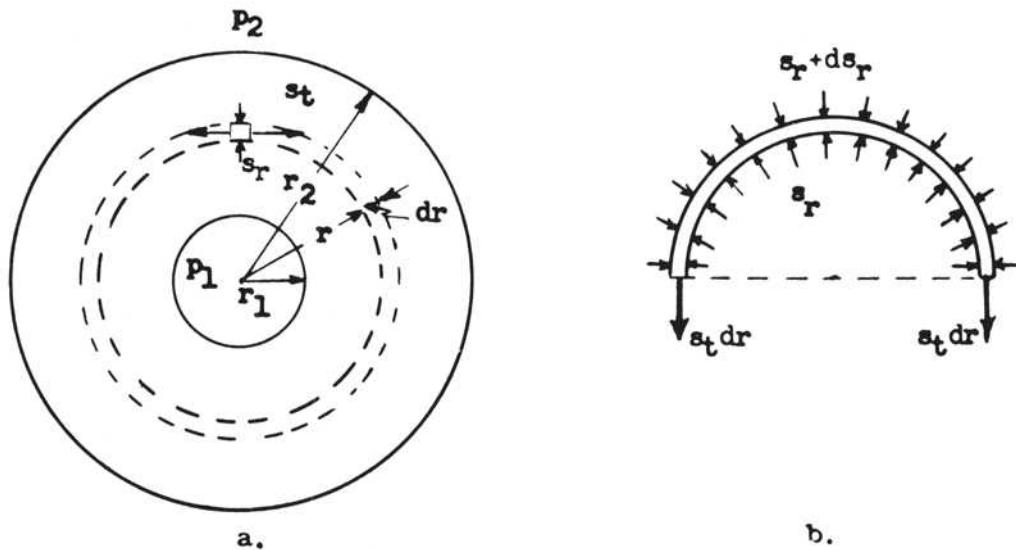
Fig. 6-4 Principal stresses in a gun tube.

a gun tube.

First, (6-4), (6-5), and (6-6) will be modified to conform more nearly to the actual case of a gun tube under the · stresses of firing. In an open cylinder there should be no principal longitudinal stress. Although a gun tube is neither a completely open nor a completely closed cylinder, it will be assumed to act as an open cylinder because it acts very nearly as one. This assumption that s_l equals zero, although not strictly true, errs on the side of safety, in that it causes the tangential strain ϵ_t, usually the deciding factor in the safety or failure of a tube, to appear larger than it actually is. With $s_l = 0$ (6-4), (6-5), and (6-6) become:

$$\Sigma_t = \Sigma \epsilon_t = s_t - \mu s_r \qquad (6\text{-}7)$$
$$\Sigma_r = E \epsilon_r = s_r - \mu s_t \qquad (6\text{-}8)$$
$$\Sigma_l = E \epsilon_l = -\mu s_r - \mu s_t \qquad (6\text{-}9)$$

These are equivalent unidirectional stresses. They are not actually existing stresses and should be clearly distinguished from the principal stresses, s_t, s_r, and s_l, which are the actual stresses to which the metal is subjected.

The values of the principle stresses s_r and s_t and their dependence on geometry and pressures inside the tube can be found by making three basic assumptions: (1) that the tube is composed of concentric thin-shelled cylinders; (2) that the strains of all longitudinal fibers of the tube are equal, i.e., that a plane transverse section remains plane and parallel to itself; and (3) that fibers act homogeneously throughout 360°

Let Figure 6-4(a) represent the cross section of a gun tube subjected to internal and external pressures p_1 and p_2, respectively. Consider (Figure 6-4 (b)) the forces acting on one-half of one of the imaginary concentric shells of which the thick cylinder is assumed to be composed. The imaginary shell has a radius r, and a thickness dr; the stress on the inner surface is s_r and that on the outer surface is $(s_r + ds_r)$, where ds_r is the increment in s_r in the distance dr due to the difference of pressure p_1 at the inner surface of the tube, and p_2 at the outer surface. Since the half shell is in equilibrium, the sum of the components, in the direction of s_t, of all forces acting on the half shell must be equal to zero; or, what is the same thing, the resultant of the forces on the inner and outer surfaces of the half shell must be equal to the total circumferential (tangential) force on a diametral plane. For convenience, the length of the shell is assumed to be unity. From these considerations the following relationship can be found.*

$$s_t = s_r + r \frac{ds_r}{dr} \qquad (6\text{-}10)$$

This equation gives one relation between s_t and s_r; another is needed to complete the solution.

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* Actually, the condition gives $2s_t dr = 2rs_r = (s_r + ds_r) (r + dr)2$, but the term $dr\, ds_r$ has been neglected, because it is very small compared to the other quantities involved.

Another relation is found by using the assumption that the longitudinal strains of all fibers are equal. The longitudinal strain of any longitudinal fiber due to the stresses s_t and s_r is

$$\epsilon_l = \frac{1}{E} \left[-\mu s_r - \mu s_t \right] \tag{6-11}$$

But ϵ_l is assumed to have the same value for all fibers, and μ and E are assumed to be constant in all axes for the material. Thus,

$$s_t + s_r = \text{a constant} \tag{6-12}$$

Let this constant be denoted by $2a$; then (6-12) becomes

$$s_t + s_r = 2a \tag{6-13}$$

yielding a second relation between s_t and s_r.

Now, by combining (6-10) and (6-13), the equation

$$2a = 2s_r + r \frac{ds_r}{dr} \tag{6-14}$$

is obtained. But the right-hand member of this equation when multiplied by r becomes the derivative, with respect to r, of $(r^2 s_r)$ and hence, the equation may be written

$$\frac{d(r^2 s_r)}{dr} = 2ar \tag{6-15}$$

The integration of this equation gives

$$r^2 s_r = ar^2 + b \tag{6-16}$$

where b is a constant of integration. Therefore,

$$s_r = a + \frac{b}{r^2} \tag{6-17}$$

and, using (6-13),

$$s_t = a - \frac{b}{r^2} \tag{6-18}$$

The values of the constants a and b are found by noting that $s_r = -p_1$ when $r = r_1$, and $s_r = -p_2$ when $r = r_2$. Substituting these values successively in (6-17) and solving the resulting equations simultaneously for a and b, one obtains the relations

$$a = \frac{p_1 r_1^2 - p_2 r_2^2}{r_2^2 - r_1^2} \quad \text{and} \quad b = \frac{r_1^2 r_2^2}{r_2^2 - r_1^2} \tag{6-19}$$

These values of a and b may now be substituted

in (6-17) and (6-18) to obtain the final objective, a pair of expressions for s_t and s_r at any point a distance r from the center of the cylinder.

The expressions are:

$$s_t = \left[\frac{p_1 r_1^2 - p_2 r_2^2}{r_2^2 - r_1^2} \right] + \left[\frac{r_1^2 r_2^2 (p_1 - p_2)}{r_2^2 - r_1^2} \right] \frac{1}{r^2} \tag{6-20}$$

and

$$s_r = \left[\frac{p_1 r_1^2 - p_2 r_2^2}{r_2^2 - r_1^2} \right] - \left[\frac{r_1^2 r_2^2 (p_1 - p_2)}{r_2^2 - r_1^2} \right] \frac{1}{r^2} \tag{6-21}$$

It is seen that the maximum value of s_t occurs at the inner surface where r has its minimum value, r_1. The stress s_r is always a compressive stress, and its maximum value will always be the larger of the two pressures p_1 and p_2.

The magnitudes of the equivalent unidirectional stresses determine the success or failure of a gun tube. Substituting the expressions given by (6-20) and (6-21) for s_t and s_r in (6-7) and (6-8) the following fundamental equations of gun tube designs are obtained:

$$\Sigma_t = E\epsilon_t = \frac{2}{3} \left[\frac{p_1 r_1^2 - p_2 r_2^2}{r_2^2 - r_1^2} \right] + \frac{4}{3} \left[\frac{r_1^2 r_2^2 (p_1 - p_2)}{r_2^2 - r_1^2} \right] \frac{1}{r^2} \tag{6-22}$$

$$\Sigma_r = E\epsilon_r = \frac{2}{3} \left[\frac{p_1 r_1^2 - p_2 r_2^2}{r_2^2 - r_1^2} \right] - \frac{4}{3} \left[\frac{r_1^2 r_2^2 (p_1 - p_2)}{r_2^2 - r_1^2} \right] \frac{1}{r^2} \tag{6-23}$$

The equation for the equivalent longitudinal stress has been omitted here, because that stress is never the decisive one in the investigation of tube safety.

Recall that these stresses are only hypothetical, that what actually exists is a state of strain whose components in the respective directions are ϵ_t, ϵ_r, and ϵ_l. Multiplications of these strains by E to obtain the equivalent unidirectional stresses given above, is simply a convenient device to enable us to use directly the elastic limit of the

gun steel in applying the basic principle of tube design. According to the maximum strain theory, if any of these equivalent stresses exceeds the elastic limit, the tube will fail.

In the above equations the independent variable is r, the radius to the point being considered; thus, for a given tube under specified pressures we can, by substituting the given conditions in the equations and varying r, investigate the condition of the stress at any radius. In all the equations a positive result for the equivalent unidirectional stress indicates tension, and a negative result indicates compression.

For a single cylinder of any dimensions, with any assumed values of p_1 and p_2, it can be shown that at the inside surface of the cylinder ($r = r_1$) there will be a combined equivalent stress equal to or exceeding in numerical value any combined equivalent stress at the outside surface of the cylinder ($r = r_2$). And this maximum equivalent stress is always one of the following, depending on the values of p_1 and p_2; tangential compression, tangential tension, or radial compression. The conditions which must be met for the equivalent radial stress to be the greatest of these is

$$1 < \frac{p_1}{p_2} < \left(\frac{r_2}{r_1}\right)^2$$

It follows that for a monobloc tube (one cylinder), where $p_2 = 0$, it is necessary to consider only the equivalent tangential stress at the inside surface in investigating the safety of the tube.

It is of interest to note that there is a maximum chamber pressure which a given caliber monobloc weapon can be designed to withstand. Increasing wall thickness will not bring a corresponding increase in allowable interior pressure. Consider (6-22) rewritten in the following form:

$$\Sigma_t = \frac{2}{3}\left[\frac{p_1 \frac{r_1^2}{r_2^2} - p_2}{1 - \frac{r_1^2}{r_2^2}}\right] + \frac{4}{3}\left[\frac{r_1^2(p_1 - p_2)}{1 - \frac{r_1^2}{r_2^2}}\right]\frac{1}{r^2} \quad (6\text{-}24)$$

For a monobloc tube, with $p_2 \cong 0$, maximum stress will occur at r_1, and (6-24) becomes,

$$\Sigma_t = \frac{2}{3}\left[\frac{p_1 \frac{r_1^2}{r_2^2}}{1 - \frac{r_1^2}{r_2^2}}\right] + \frac{4}{3}\left[\frac{p_1}{1 - \frac{r_1^2}{r_2^2}}\right] \quad (6\text{-}25)$$

Similarly, the allowable pressure

$$p_1 = \frac{3}{2}\Sigma_t\frac{r_2^2 - r_1^2}{r_1^2 + 2r_2^2} = \frac{3}{2}\Sigma_t\left[\frac{1 - \frac{r_1^2}{r_2^2}}{\frac{r_1^2}{r_2^2} + 2}\right]$$

If r_2 is made very much larger than r_1, then

$$p_1 = \frac{3}{4}\Sigma_t \quad (6\text{-}26)$$

Equation (6-26) illustrates that for a very thick walled cylinder, if interior pressure exceeds ¾ the elastic limit of the metal, the cylinder will deform inelastically, and further increase of r_2 will not contain a greater interior pressure.

Figure 6-5 illustrates Σ_t as a function of maximum allowable interior pressure in terms of wall thickness expressed in calibers.
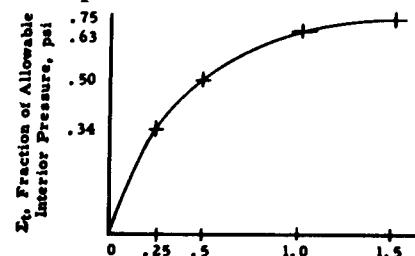
Fig. 6-5 Effect of wall thickness on allowable maximum powder pressure.

6-5 SOME ILLUSTRATIVE EXAMPLES

(a) Interior Pressure Only (Figure 6-6). Consider a tube in which

$r_1 = 0.2$ in.
$r_2 = 0.5$ in.

$p_1 = 50,000$ psi
$p_2 = 0$

These are approximately the conditions at the chamber of the cal. .30 rifle, M-1, when the rifle

is fired. Substituting the values above into (6-22) the equivalent tangential stress is found to be:

$$\Sigma_t = \frac{2}{3}\left(\frac{50{,}000(0.2) - 0(0.5)^2}{(0.5)^2 - (0.2)^2}\right)$$

$$+ \frac{4}{3}\left(\frac{(0.2)^2(0.5)^2(50{,}000 - 0)}{(0.5)^2 - (0.2)^2}\right)\frac{1}{r^2}$$

$$= 6350 + 3175\frac{1}{r^2}$$

At the inside surface ($r = r_1 = 0.2$ in.)

$$\Sigma_{t_{r_1}} = 85{,}725 \text{ psi (tension)}$$

At the outside surface ($r = r_2 = 0.5$ in.)

$$\Sigma_{t_{r_2}} = 19{,}050 \text{ psi (tension)}$$

Intermediate points on the stress versus radius curve may be found by using intermediate values of r. The curve is concave upward (Figure 6-6(a)).

A graph of the equivalent radial stresses is shown in Figure 6-6(b). Values for this curve are obtained by making, in (6-23), the same substitutions used above. It is seen that all the stresses obtained are well within the elastic limit of gun steels, which in many cases, exceeds 100,000 psi.

(b) Interior Pressure Only. Consider the design of an 8-inch gun tube ($r_1 = 4$ in.) to withstand the same interior pressure as the M-1 barrel above. Further, suppose that the maximum equivalent tangential stress is not to exceed that obtained above in the case of the M-1, namely, 85,725 psi, i.e., assume the same elastic limit and the same factor of safety. How thick must the wall be? Will the same thickness, 0.3 inches, be sufficient? Substituting the values

$$r_2 = x$$
$$r = r_1 = 4 \text{ in.}$$
$$p_1 = 50{,}000 \text{ psi}$$
$$p_2 = 0$$

into (6-22)

$$\Sigma_{t_{r_1}} = 85{,}725 = \frac{2}{3}\left[\frac{50{,}000(4)^2 - 0(x)^2}{(x)^2 - (4)^2}\right]$$

$$+ \frac{4}{3}\left[\frac{(4)^2(x)^2(50{,}000 - 0)}{(x)^2 - (4)^2}\right]\frac{1}{(4)^2},$$
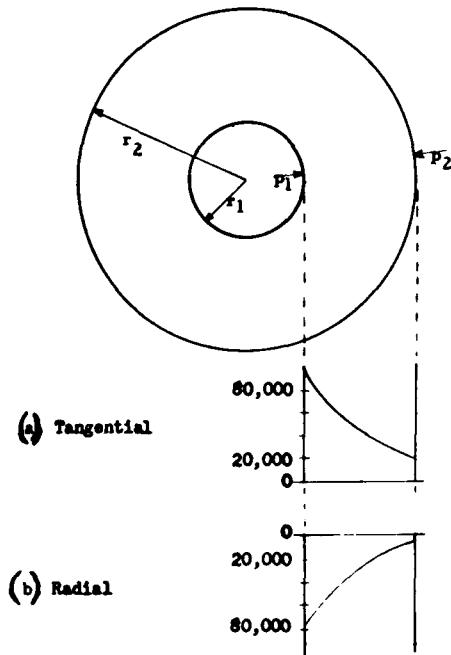
Fig. 6-6 Equivalent unidirectional stresses.

whence $x = 9.998$ in. $= r_2$.

This means that the 8-inch gun tube must have a wall thickness of almost 6 inches if it is to contain as much pressure as the M-1 rifle, with its 0.3-inch wall. Actually, for a given interior pressure and elastic limit the wall thickness is proportional to the inside radius. The 8-inch gun tube, under these conditions, would be excessively large (approximately 20 inches, outside diameter) and heavy. Practically, we must reduce the pressure, get higher strength steels, use other techniques of design, or follow a combination of these procedures to overcome this difficulty and make the gun sufficiently light and mobile. Note that it is the inner fibers of the gun tube that bear most of the stress. We would gain in tube strength if the outer fibers could be utilized more fully.

(c) Both Interior and Exterior Pressures. Assume that, by some means, an exterior pressure of 20,000 psi can be applied to the 8-inch gun

tube of the preceding example. What should the thickness of the wall be then?

From (6-16):

$$\Sigma_{t_{r_1}} = 85,725 = \frac{2}{3}\left[\frac{50,000(4)^2 - 20,000(x)^2}{(x)^2 - (4)^2}\right]$$

$$+ \frac{4}{3}\left[\frac{(4)^2(x)^2(50,000 - 20,000)}{(x)^2 - (4)^2}\right]\frac{1}{(4)^2}$$

whence

$$x = 5.679 \text{ in.} = r_2.$$

(Only the equivalent tangential stress has been considered as a basis for this calculation, because it is the largest equivalent stress in this case. In general, however, one should examine a problem carefully to ascertain whether or not this is so.) We have now a wall thickness of 1.679 inches, as compared to the 6-inch wall needed when no exterior pressure was applied. The outer fibers have been utilized more fully; but we have yet to work out the means for applying the external pressure. These means usually involve adding components with considerable weight, but there is still a large net reduction in weight.

6-6 BUILT-UP GUNS

To put the lesson of examples (b) and (c), Par. 6-5 in another form, the equivalent stresses, both tangential and radial, set up in a gun tube of prescribed radius and wall thickness by the action of an interior pressure, may be greatly reduced if an exterior pressure is caused to act at the same time. (Similarly, the equivalent stresses due to an exterior pressure are modified if an interior pressure acts at the same time.) This implies that, if the tube could be squeezed initially causing tangential compression, then the internal gas pressure applied when firing takes place would first have to overcome this compression in the tube before it could stretch the tube tangentially in tension (Figure 6-7). This would succeed in extending the range of allowable gas pressure with the same weight and wall thickness of tube, solving one of the designer's major problems.

There are several ways in which this idea has been put to use in actual gun design. The external pressure may be applied by a tight wrapping of high tensile strength wire around the tube. A cold-working process, to be discussed later, in which a tube forging or casting is initially stressed by applying hydraulic pressure to the inside of the bore, is, in part, another application of this idea. Still another way of obtaining this desired squeeze on a gun tube involves the shrinking of a concentric cylinder, called a jacket or a hoop, around the tube. In this method the inside diameter of the jacket is made slightly smaller than the outside diameter of the tube.

The jacket is then expanded by heat until it fits over the tube. Later, as it cools, the jacket tries to shrink back to original size and so squeezes the tube into a state of compression. More than one jacket may be used where necessary. This solution to the problem is called the built-up method of gun construction.

When a built-up gun is at rest (not firing) there is, considering tangential stresses, a compressive stress on the tube due to the shrunk jacket and a tensile stress in the jacket due to the tube. When the gun is fired there is developed, in addition to the stresses mentioned above, tangential tensile stress in both tube and jacket due to the gas pressure within the bore. It is the algebraic sum of these superimposed effects which must not exceed safe limits if the gun is to succeed. In both the rest condition and the firing condition, the radial stresses in the tube and jacket are compressive and again, the sum of the stresses under the two superimposed conditions must be within prescribed limits. According to the condition stated in Par. 6-4, it is necessary to consider the following cases in investigating the safety of the components of a built-up gun:

(1) For the tube (and any interior jackets), the equivalent tangential and radial stresses at the inside surface.

(2) For the (exterior) jacket ($p_2 = 0$), only the equivalent tangential stress at the inside surface.
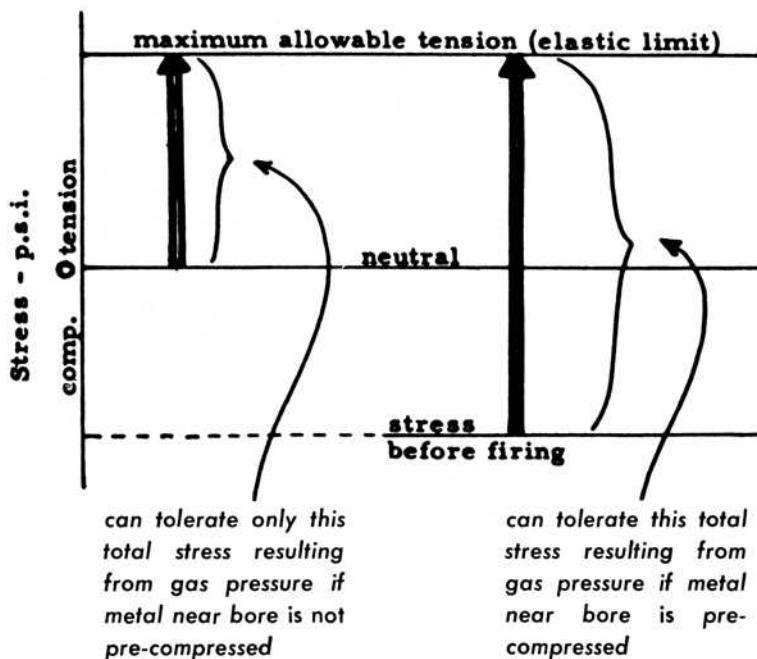
Fig. 6-7 Effect of precompression.

6-7 CALCULATIONS IN BUILT-UP GUNS

When a built-up gun is at rest (Figure 6-8), the only stresses present result from the shrinkage pressure (p_s). Maximum compressive tangential stress occurs at the inner surface of the tube, and maximum tangential tensile stress occurs at the inner surface of the jacket. To find the tangential and radial equivalent stresses on the tube and jacket (6-22) and (6-23) must be applied separately to the tube and to the jacket, taking care to use the pressures and radii appropriate to the element considered.

There are two free body diagrams that apply to the built-up gun at rest (Figure 6-9).

When the gun is in action there is superimposed a stress condition due to the gas pressure in the bore. This stress is computed as if the tube and jacket were simply a single piece (Figure 6-10).

The total stress at any point when the gun is in action is then the algebraic sum of the stress due to shrinkage pressure and the stress due to gas pressure. The stresses throughout the tube and jacket when the gun is in action are obtained,

Fig. 6-8 Σ_t due to shrinkage pressure only (symbol Σ_{ts}).

$p_1 = 0$ (atmospheric)
$p_2 \doteq p_s$ (shrinkage
pressure)
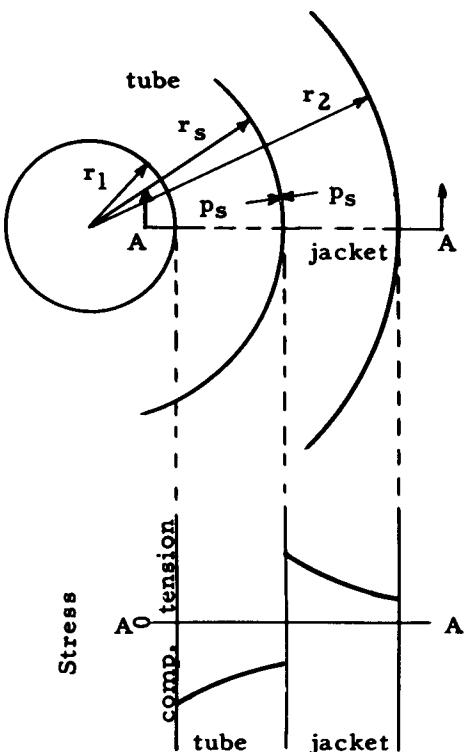
$p_1 = p_s$ (shrinkage
pressure)
$p_2 = 0$ (atmospheric)
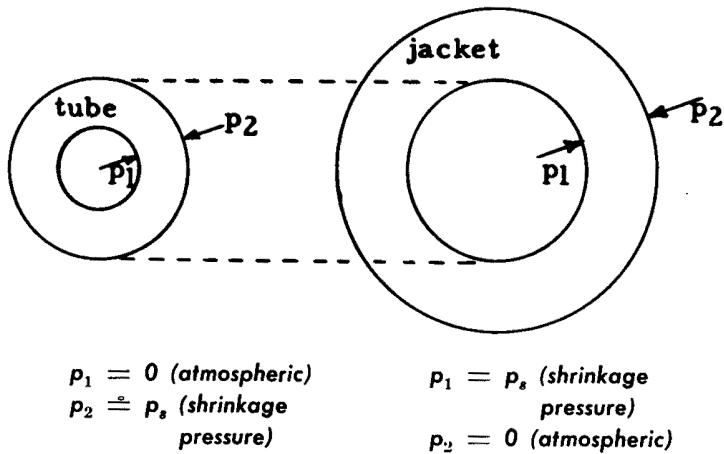
Fig. 6-9 Gun at rest.
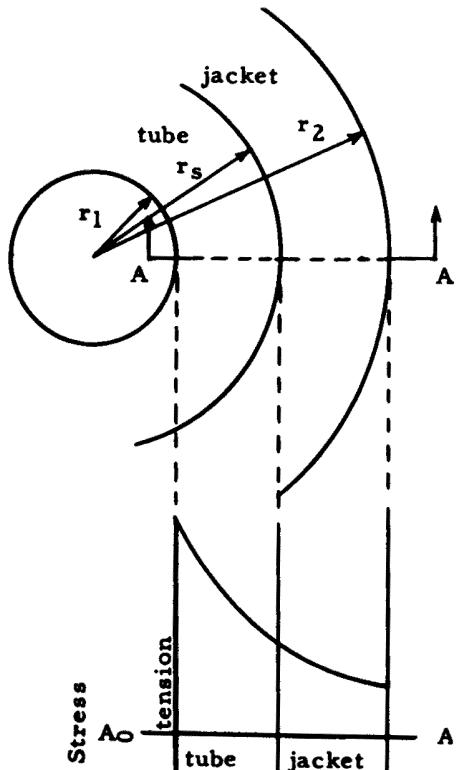
Fig. 6-10 Σ_t due to powder gas pressure
only (symbol Σ_{tg}).

Fig. 6-11 Σ_t when gun is in action (Σ_{ta}).
$\Sigma_{ts} = \Sigma_t$ due to shrinkage
pressure;
$\Sigma_{tg} = \Sigma_t$ due to propellant
pressure.

therefore, by combining the curves in Figures 6-8 and 6-10 (see Figure 6-11).

It is apparent from the above figures that by putting the metal of the tube in an initial state of compression there can be tolerated a change in stress due to gas pressure (Σ_{tg}) which is greater than the elastic limit of the metal, and yet the metal is not actually stressed beyond its elastic limit. Note that if the tube and jacket are considered as a unit, then we have put the outer fibers of the unit to work to a greater degree to relieve the hard-pressed inner fibers.

To summarize, in solving built-up problems:

(a) To determine any stress caused by shrinkage pressure only, consider tube and jacket separately.

(b) To determine any stress caused by pro-pellent gases only, consider tube jacket as one cylinder.

(c) To determine any stress caused by gas pressure and shrinkage pressure jointly, combine steps (a) and (b) above.

6-8   ILLUSTRATIVE PROBLEM

GIVEN: A section of a two cylinder built-up gun with dimensions and pressures as indicated.
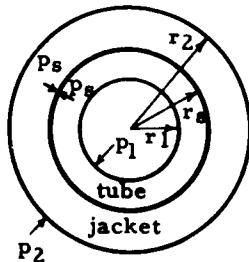
$r_1 = 3$ in.
$r_s = 5$ in.
$r_2 = 8$ in.
$p_s = 8907$ psi

With the gun in action the powder gas pressure is 40,000 psi

REQUIRED: Find the maximum equivalent tangential stress in the tube and the jacket with the gun in action (Σ_{ta}).

SOLUTION: The in-action stress in any part of the gun has two components: (1) that due to shrinkage pressure, and (2) that due to gas pressure. Find each component separately and add them algebraically. Maximum stress for the tube will occur at the inner radius (r_1) and for the jacket at r_s.

The problem can most conveniently be solved by constructing a table similar to Table 6-1.

Thus the stresses at the inner radius of the tube and jacket, at rest and in action, can be computed using (6-22). Total in-action stresses can then be computed by adding algebraically the stress due to shrinkage pressure at either radius to the stress due to gas pressure at the same radius. Successive substitution of the values in the table into (6-22) yields the following:

$$\Sigma_{ts1} = -27,800 \text{ psi}$$
$$\Sigma_{tg1} = 66,400 \text{ psi}$$
$$\Sigma_{ts2} = 23,330 \text{ psi}$$
$$\Sigma_{tg2} = 26,670 \text{ psi}$$

Thus it is seen that the in-action stress at r_1 is

$$\Sigma_{ta} = 66,400 - 27,800 = 38,600 \text{ psi}$$

TABLE 6-1   CALCULATION FOR IN-ACTION STRESS

Cylinder Considered	Pressure Due to	R_1	R_2	R	P_1	P_2	Σ_t
Tube	Shrinkage (Rest)	3	5	3	0	8907	Σ_{ts1}
Only	Gas (In Action)	3	8	3	40,000	0	Σ_{tg1}
Jacket	Shrinkage (Rest)	5	8	5	8907	0	Σ_{ts2}
Only	Gas (In Action)	3	8	5	40,000	0	Σ_{tg2}

Similarly the in-action stress at r_s is

$\Sigma_{ta} = 26,670 + 23,300 = 50,000$ psi

For the built-up gun, then, maximum stress

will not necessarily occur at the inner radius, but may occur at the surface between the tube and the jacket.

6-9 EFFECT OF OVERSTRAIN OF METAL

Another method for obtaining greater pressure limits for gun tubes, a cold-working process, depends for its strengthening of the tube partly upon a jacketing effect, putting the fibers near the bore in a state of compression, and partly upon an increased elastic limit in the metal due to the cold-working. While the method itself will be discussed in the following paragraph, it will be helpful to review beforehand its underlying principle and recall briefly what happens when a metal is overstrained, but not to the point of rupture.

When the elastic limit of metal is exceeded, the proportionality between stress and strain, which existed below the elastic limit, no longer holds true. The metal becomes partially plastic, showing an increased but varying ratio of strain to stress. The stress-strain diagram shown in Figure 6-12 illustrates the influence of cold-working on elastic limit and yield strength. If the stress applied to this steel is carried beyond the elastic limit located at A to some point B and then released, the metal will partially regain its original size along the path BG (Parallel to AO),

and OG will then represent the resultant permanent deformation. If the metal is now restressed, it will follow the new path of elastic deformation GB, and permanent deformation will begin, this time at B. Thus the new elastic limit at B is at a higher stress than the original, and the yield strength is correspondingly increased. In obtaining these gains, however, part of the ductility and toughness of the metal is sacrificed.
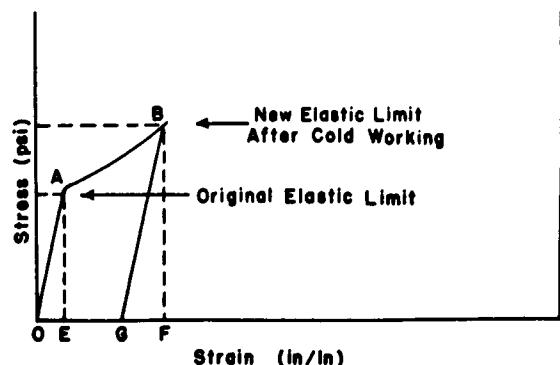
Fig. 6-12 Typical stress-strain diagram for cold-worked gun steel.

6-10 COLD-WORKED GUN TUBES

As was mentioned earlier, a cold-worked gun tube has increased elastic strength due to two causes. Part of the gain is due to strain hardening, discussed in Par. 6-9, and shows up as an actual increase in the yield strength which can be measured by tensile tests. The remainder of the gain results from the residual tangential stresses left in the material after the pressure is released.

In the cold-working process the unfinished tube, without being heated, is stressed beyond its elastic limit by hydraulic pressure applied to the bore. According to Par. 6-9 and Figure 6-12,

when the hydraulic pressure is released the tube is left with some permanent set and an increased elastic limit. Figure 6-13 shows the tangential stresses involved in a typical cold-worked tube, plotted as functions of the radius. (It has been stated in Par. 6-4 that, with only interior pressure acting, the equivalent stress is greatest in the tangential direction.)

The new elastic limit, coinciding approximately with the stress developed during cold-working, is shown by curve (a). Note that it is not constant throughout the wall of the tube, but decreases as the radius increases, being greatest at the inner
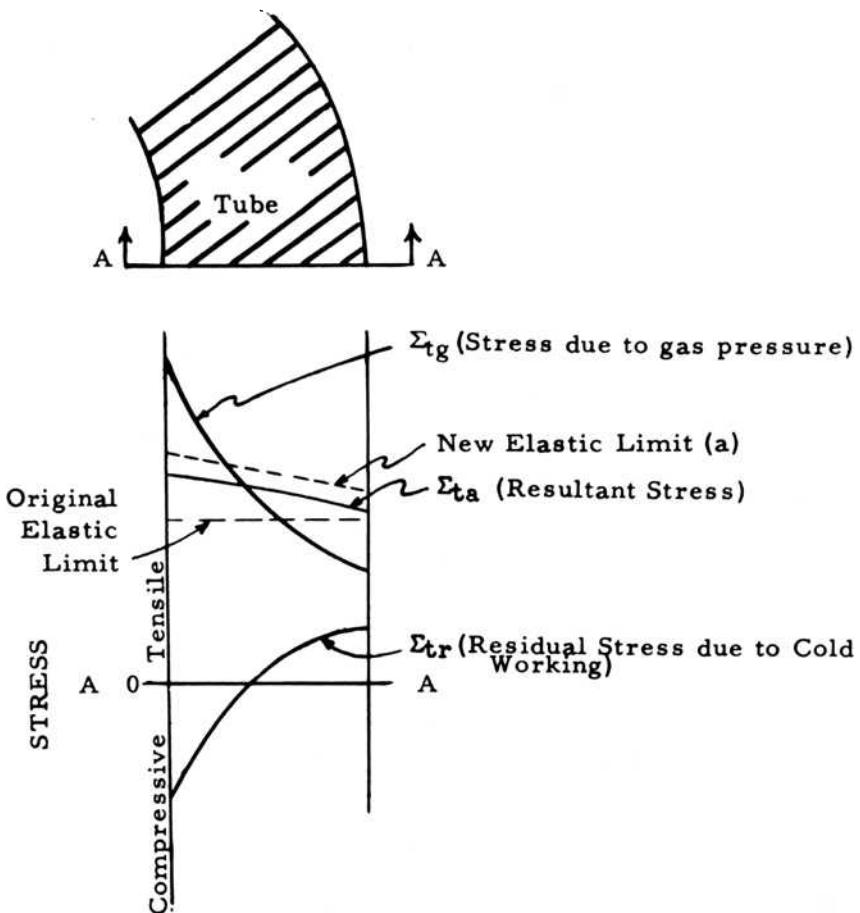
Fig. 6-13 Stresses in cold-worked tube.

surface where the metal was overstrained the most. The permanent set caused by the overstrain, also greatest where the overstrain was the greatest, causes the fibers toward the inside of the tube to resist the attempt of the outer fibers to return more nearly to the original dimension. Thus, the metal of the tube contains internal stresses called residual stresses, and the metal near the bore is in compression while th .t near the outside surface is in tension. Curve (b) shows a typical distribution of these residual stresses. For equilibrium, the curve must cross the axis of zero stress at some point r_0, and the area between the tension branch of the curve and the axis must equal the area between the compression branch and the axis. This residual stress corresponds to the shrinkage stress in the cylinders of a built-up gun at rest In fact, a cold-worked gun will have the same distribution of residual stress as would be found in a gun built-up of an infinite number of layers.

The actual stresses in a built-up gun in action a.e the algebraic sum of the stresses due to shrinkage (residual stresses in a cold-worked gun) and those due to the propellent gas pressure. Exactly the same principle holds true for the cold-worked gun. Thus, the equivalent stress when the gun is in action, Σ_{ta}, is obtained by adding algebraically the equivalent stress due to gas pressure, Σ_{tg}, and the residual stress, curve (b). The in-action stress Σ_{ta} must not exceed the new elastic limit, curve (a), if the gun is to succeed. In computing stress due to gas pressure, the equations developed earlier in this chapter are applicable because the metal is perfectly elastic within its new elastic limit.

The effect due to the residual stresses is known

by the French name autofrettage, which means, literally, self hooping. From Figure 6-13, it is seen that there is a hoop of residual tension on the outside and a hoop of residual compression at the bore. The entire process described in this paragraph, as a matter of fact, is sometimes called the autofrettage process.

The autofrettage process as used by the U.S. Navy and foreign nations, however, involves lower pressures with smaller expansion than that employed by the U.S. Army. In those processes, strength is gained largely from autofrettage with little being gained from strain hardening. To differentiate, the Army generally speaks of its process as cold-working.

A thick-walled cylinder which has been cold-worked, and then properly heat-treated, will withstand the subsequent application of any bore pressure which does not exceed the pressure applied to accomplish the cold-working. In general, the allowable pressure is almost doubled. Of this increase, about half is due to the increase in the elastic limit and the other half to the residual stress condition.

6-11 THIN WALLED CYLINDERS

The equations of Par. 6-4 are applicable to cylinders regardless of wall thickness. If the wall thickness is decreased in proportion to the inner radius until it is in the vicinity of 1/10 the radius, (6-20) can be greatly simplified.

Consider (6-20), letting $r = r_1$ in order to obtain maximum tangential stress.

$$s_t = \frac{p_1 r_1^2 - p_2 r_2^2}{r_2^2 - r_1^2} + \frac{p_1 r_2^2 - p_2 r_2^2}{r_2^2 - r_1^2}$$

Now let $p_2 = 0$, the case when external pressure is atmospheric and internal pressure much greater than atmospheric,

$$s_t = \frac{p_1(r_2^2 + r_1^2)}{r_2^2 - r_1^2} = \frac{p_1 r_1}{r_2 - r_1}\left[\frac{\frac{r_2^2}{r_1} + r_1}{r_2 + r_1}\right]$$

$$= \frac{p_1 r_1}{r_2 - r_1}\left[\frac{\left(\frac{r_2}{r_1}\right)^2 + 1}{\left(\frac{r_2}{r_1}\right) + 1}\right] \qquad (6\text{-}27)$$

as $\frac{r_2}{r_1} \to 1$, it can be seen that

$$s_t \to \frac{p_1 r_1}{r_2 - r_1}$$

The following table lists values of the ratio $\frac{s_{t\,thick}}{s_{t\,thin}}$ for decreasing values of $\frac{r_2}{r_1}$.

$\dfrac{r_2}{r_1}$	2	1.5	1.3	1.2	1.15	1.1	1.05
$\dfrac{s_{t\,thick}}{s_{t\,thin}}$	1.67	1.3	1.17	1.11	1.08	1.05	1.03

From this table it can be seen that if wall thickness is less than 1/10 the inner radius, tangential stress can be calculated using this simplified relationship

$$s_t = \frac{p_1 r_1}{r_2 - r_1} \qquad (6\text{-}28)$$

The resulting error is about 5 percent.

Since r_2 is very nearly equal to r_1 in the thin walled cylinder, tangential stress is considered to be uniform across the wall of the cylinder. Furthermore, from (6-21), radial stress at r_1 is equal to p_1, the internal pressure. From (6-28)

$$s_t = \frac{p_1}{\frac{r_2}{r_1} - 1}$$

If $\frac{r_2}{r_1}$ is only slightly greater than 1, s_t will be much greater than p_1, and consequently s_r. For this reason, radial stresses in a thin walled cylinder can be neglected.

It remains only to evaluate p_1, the internal pressure, to determine stresses in the wall of a thin walled cylinder.

6-12   STRESSES IN A ROTATING PROJECTILE

Before a projectile can be soundly designed, the forces which act on it and the stresses they produce must be thoroughly understood. This requires more than just familiarity with the formulas involved, for until the nature of the stresses resulting from setback and centrifugal force is mastered, no intelligent approach to the design problem can be made.

In high explosive shells the designer endeavors to produce a projectile with adequate wall strength and yet capable of holding the greatest amount of explosive filler possible. Naturally, each of these factors interferes to some extent with the other, and hence some compromise must be made. The question, then, is how thick the projectile wall must be to withstand, without failure, the maximum resultant stress set up by all the forces acting.

Assuming that the strongest most suitable material is used, the problem reduces to one of determining the optimum wall thickness for every section of the projectile. Examination of standard projectiles which have been sectionalized will reveal that shell walls are not of uniform thickness throughout, but rather, thickest wherever the overall resultant stress is greatest. For obvious reasons, stresses in projectile walls are calculated by sections, and the following discussion of the forces encountered and the nature of the stresses they produce is presented as a practical aid towards understanding and applying design formulas.

When a projectile under the action of the propellent gases moves forward in the bore, the property of inertia causes it to resist any force which tends to move it. This resistance naturally sets up within the projectile walls stresses whose magnitude in any section depends upon the mass ahead of that section and the acceleration of the projectile at the instant under consideration. The force which produces these stresses is called setback, and for any section, is a maximum for that section when the acceleration is greatest; that is, at the instant the propellent gas pressure reaches its maximum value (Figure 6-14).

The setback force also affects the explosive filler but not in the same way, for this substance behaves more like a liquid than it does a solid. In this connection, setback produces within the explosive charge a hydraulic pressure which is transmitted equally in all directions. Of special significance is the hydraulic pressure which is transmitted radially against the shell wall producing additional stresses therein.

In addition to translation, the rapidly expanding propellent gases cause the rifling to impart rotation to the projectile, a factor which results in wall stresses created in two slightly different ways. One set of stresses results from centrifugal force acting on the wall itself while the other set is produced by centrifugal force acting on the explosive filler, causing it to exert an additional pressure on the shell wall.
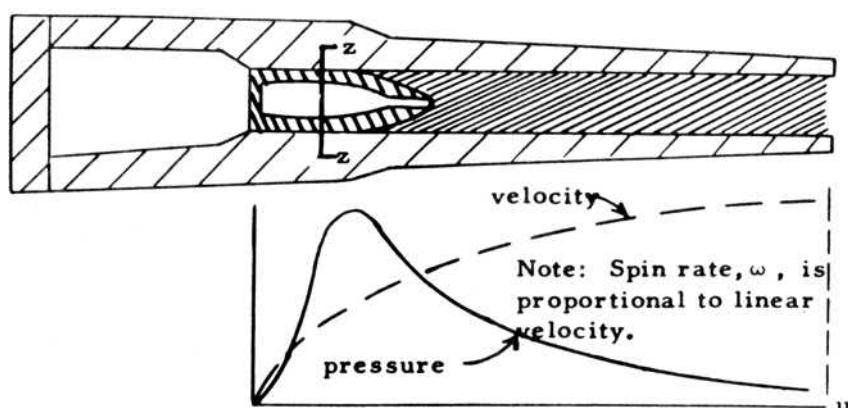
Fig. 6-14 Velocity and pressure as functions of projectile travel.

6-13 CALCULATIONS

6-13.1 STRESSES RESULTING FROM SETBACK

(a) Setback of projectile exclusive of explosive filler.

Stresses calculated previously in this chapter had as their basis a uniformly distributed internal and/or external pressure. When a projectile is subjected to setback, there is a stress induced in the wall due to the inertia of the wall. This stress is longitudinal and compressive. The calculation of this stress involves first the determination of the force exerted on a transverse section by the accelerated weight of that portion of the projectile ahead of this section. This force is then divided by the area of the section to determine the stress.

(b) Stress in projectile walls resulting from setback of explosive filler.

Since the explosive filler acts as a fluid (Par. 6-12) it will exert a pressure radially against the projectile walls. This pressure must be calculated; then (6-28) can be used to find the tangential stress.

6-13.2 STRESSES RESULTING FROM ROTATION

(a) Resultant tangential stress in projectile walls due to rotation of the explosive filler.

This stress is determined by calculating the centrifugal force exerted by the filler, and dividing by the area over which it is distributed to determine the pressure on the walls, p_f. Equation (6-28) will then give the stress due to this internal pressure.

(b) Tangential stress in shell walls due to rotation of the projectile.

This stress is calculated by determining centrifugal force exerted by the projectile wall as a function of radius. The total tangential force acting is then calculated by double integration. The tangential stress can then be found by dividing this tangential force by the area over which it is acting.

ILLUSTRATIVE EXAMPLE

Calculate the stresses acting at section $z - z$ (Figure 6-14) in a projectile wall given the following data:

R = caliber = 3 in.
P = maximum propellant pressure = 20,000 psi
W = weight of projectile = 12 lb
W^1 = weight of projectile ahead of section $z - z$ = 6 lb
t = wall thickness at section $z - z$ = 1/4 in.
Δ_1 = density of filler = 0.006 lb/in^3
l = distance l (Figure 6-15; consider to be cylindrical) = 6 in.
v = muzzle velocity = 1700 ft/sec
n = rifling: 1 turn in 25 calibers
Δ_2 = density of steel in wall = 0.3 lb/in^3
r_1 = inner wall radius = 1.25 in.
r_2 = outer wall radius = 1.5 in.
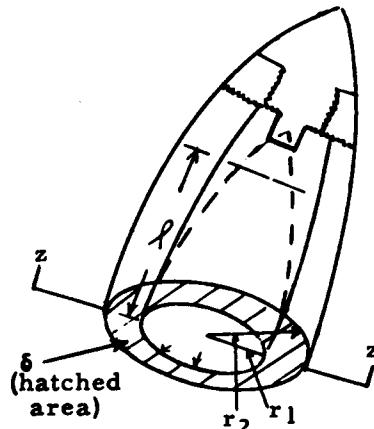
Fig. 6-15 Stress in projectile wall due to setback acting on projectile.

Additional symbols to be used

A = cross-sectional area of bore, in.^{2}
a = acceleration of projectile, ft/sec^2
δ = cross-sectional area of the projectile wall at section $z - z$, in.^{2}
f = longitudinal force in projectile wall due to setback, lb
W_f = weight of explosive filler ahead of section $z - z$ lb
P_h = hydraulic pressure exerted by W_f, psi
F_n = centrifugal force of filler against projectile wall, lb
P_f = pressure against wall due to centrifugal force acting on filler, psi

ω = angular velocity of projectile at muzzle, radians/sec

F_r = centrifugal force exerted by projectile body, lb

F_t = tangential force resulting from F_r, lb

SOLUTION

(1) First calculate the stress s_1 in the projectile wall due to setback acting on the projectile.

$$s_1 = \frac{f}{\delta} = \frac{(W^1/g)x(a)}{\delta}$$

but

$$a = \frac{PAg}{W}$$

therefore

$$s_1 = \frac{W^1PA}{W\delta} = \frac{W^1PA}{W\pi(r_2^2 - r_1^2)}$$

$$= \frac{6 \times 20,000 \times \pi \times 1.5^2}{12 \times \pi(1.5^2 - 1.25^2)}$$

$$= 32,700 \text{ psi (compressive)}$$

(2) Calculate the stress s_2 due to setback acting on the explosive filler.

$$s_2 = P_h \frac{r_1}{r_2 - r_1} = \frac{W_f a}{g} \times \frac{1}{\pi r_1^2} \times \frac{r_1}{r_2 - r_1}$$

$$= \frac{\Delta_1 \times \pi r_1^2 \times l \times \dfrac{PAg}{W}}{g} \times \frac{1}{\pi r_1^2} \times \frac{r_1}{r_2 - r_1}$$

$$= \frac{\Delta_1 \times l \times P \times A}{W} \times \frac{r_1}{r_2 - r_1}$$

$$= \frac{0.06 \times 6 \times 20,000 \times \pi \times 1.5^2}{12} \times \frac{1.5}{\tfrac{1}{4}}$$

$$= 21,210 \text{ psi}$$

(3) Calculate the stress s_3, due to centrifugal force acting on the explosive filler.

$$s_3 = p_f \frac{r_1}{r_2 - r_1} = \frac{F_n}{2\pi r_1} \frac{r_1}{r_2 - r_1}$$

but

$$F_n = \frac{M r_1 \omega^2}{12}$$

$$M = \frac{\Delta_1 \pi_1^2}{g} \text{ per unit length}$$

therefore

$$p_f = \frac{\Delta_1 r_1^2 \omega^2}{24g}$$

now

$$\omega(\text{rad/sec}) = \frac{12\pi v}{nR}$$

$$= \frac{2\pi(\text{rad/turn}) \times v(\text{ft/sec}) \times 12(\text{in./ft})}{2R(\text{in./cal}) \times n(\text{cal/turn})}$$

$$= \text{rad/sec}$$

then

$$p_f = \frac{6\pi^2 \Delta_1 r_1^2 v^2}{g n^2 R^2}$$

$$p_f = 1.84 \Delta_1 \left(\frac{v r_1}{nR}\right)^2$$

$$p_f = 1.84 \times .06 \left(\frac{1700 \times 1.25}{25 \times 1.5}\right)^2 = 354 \text{ psi}$$

$$s_3 = 354 \times \frac{1.25}{1.5 - 1.25} = 1770 \text{ psi}$$

(4) Calculate the tangential stress s_4, due to rotation of the projectile body (Figure 6-16).
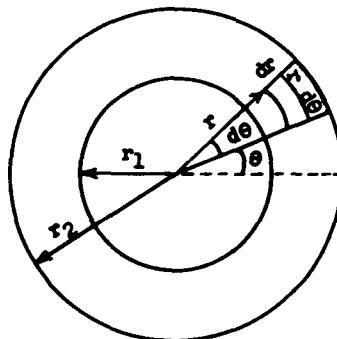
Fig. 6-16 Cross section of projectile wall of unit length. Calculation of stress in wall due to centrifugal force acting on projectile.

$$F_r = \frac{Mr_\omega^2}{12}$$

$$dF_r = \frac{r_\omega^2 dM}{12}$$

but

$$dM = \frac{\Delta_2 r \, dr \, d\theta}{g} \text{ (per unit length)}$$

$$dF_r = \frac{\omega^2 \Delta_2 r^2 \, dr \, d\theta}{12g}$$

now

$$dF_t = dF_r \sin\theta$$

$$dF_t = \frac{\omega^2 \Delta_2}{12g} r^2 \sin\theta \, dr \, d\theta$$

$$F_t = \frac{\omega^2 \Delta_2}{12g} \int_{r_1}^{r_2} \int_0^\pi r^2 \sin\theta \, dr \, d\theta$$

$$= \frac{\omega^2 \Delta_2}{12g} \int_{r_1}^{r_2} r^2 \, dr \left[-\cos\theta \right]_0^\pi$$

$$F_t = \frac{\omega^2 \Delta_2}{6g} \int_{r_1}^{r_2} r^2 \, dr \, .$$

$$F_t = \frac{\omega^2 \Delta_2 (r_2{}^3 - r_1{}^3)}{18g}$$

$$s_4 = \frac{F_t}{2(r_2 - r_1)}$$

$$s_4 = \frac{\omega^2 \Delta_2 (r_2 - r_1)(r_2{}^2 + r_2 r_1 + r_1{}^2)}{36g(r_2 - r_1)}$$

$$s_4 = \frac{\omega^2 \Delta_2 (r_2{}^2 + r_2 r_1 + r_1{}^2)}{36g}$$

Let

$$c = \frac{r_1}{r_2} = 0.833 \text{ for this problem}$$

then

$$cr_2 = r_1$$

and

$$s_4 = \frac{\omega^2 \Delta_2 (r_2{}^2 + cr_2{}^2 + c^2 r_2{}^2)}{36g}$$

$$= \frac{\omega^2 \Delta_2 r_2{}^2 (1 + c + c^2)}{36g}$$

now

$$\omega = \frac{12 \pi v}{n R} ;$$

then

$$s_4 = \frac{4 \pi^2}{g} (1 + c + c^2) \Delta_2 \left(\frac{V}{n}\right)^2 \left(\frac{r_2}{R}\right)^2$$

Let

$$K = \frac{4 \pi^2}{g} (1 + c + c^2) = 3.4 \text{ for this problem}$$

For most sections of the projectile $\frac{r_2}{R}$ is very nearly unity.
Then

$$s_4 = K \Delta_2 \left(\frac{V}{n}\right)^2$$

When $c = 1$ (viz, $r_1 = r_2$ and the shell wall has no thickness), the upper limit of K may be established as:

$$K = \frac{4 \pi^2}{g} (1 + 1 + 1) = 3.68$$

then

$$s_4 = K \Delta_2 \left(\frac{V}{n}\right)^2$$

$$s_4 = 3.4 \times 0.3 \left(\frac{1700}{25}\right)^2$$

$$= 4710 \text{ psi}$$

6-14   CALCULATION OF EQUIVALENT UNIDIRECTIONAL STRESS

Having determined the individual stresses acting on section z-z of the shell wall due to setback and centrifugal force, it is now possible by using (6-4), (6-5), or (6-6) to determine the equivalent unidirectional stress which we may use to determine if the projectile wall will fail. The stresses as computed are:

s_1 (longitudinal) = $-32,600$ psi
s_2 (tangential)   = $21,210$ psi
s_3 (tangential)   = 1770 psi

s_4 (tangential)   = 4710 psi

Substituting these stresses into (6-6)

$$\Sigma_l = s_l - \frac{s_r}{3} - \frac{s_t}{3} = -32,600 - \frac{(27,690)}{3}$$

$$= -41,830$$

Some appropriate failure criterion must now be applied to determine if this equivalent stress is within allowable limits.

6-15 OTHER APPLICATIONS

Although the specific examples discussed in this chapter have been entirely from the field of artillery, the principles are equally applicable to any cylinder subjected to wall stresses. Thus, the stresses developed in the walls of a missile fuel tank would be analyzed on the same basis. The magnitudes of the forces might be greatly different (rotational speed and linear acceleration are very much less in most missiles) but the problem is essentially the same; i.e., developing a structure with the minimum weight to perform the job adequately and safely.

Similarly, rocket engines subjected to interior pressures can be analyzed using the equations of Par. 6-4 or of Par. 6-11 depending upon the wall thickness of the motor.

REFERENCES

1 Hayes, *Elements of Ordnance*, New York: John Wiley and Sons, Inc., 1938, pp. 153-240.

2 Seely, *Resistance of Materials*, New York: John Wiley and Sons, Inc., Third edition, 1947, pp. 42-47, 388-397.

3 Singer, *Strength of Materials*, New York: Harper and Brothers, 1951, pp. 39-45, 414-419.

4 Department of the Army, Technical Manual, TM9-2305, *Fundamentals of Artillery Weapons*, Washington, U.S. Government Printing Office, 1947, pp. 1-37.

CHAPTER 7

RECOIL SYSTEMS

7-1 GENERAL

The stresses to which a gun carriage is subjected are caused by the action of the propellent gases on the breech of the gun itself. The force tending to move the gun to the rear may be very large, amounting to several million pounds in the major caliber weapons. If the gun were mounted rigidly, i.e., without any recoil system, so that neither gun nor carriage could move, it would be most difficult to build a carriage strong enough to withstand the firing stresses without rupture or overturning. Or, if the gun were mounted on a mobile carriage without a recoil system, the entire gun and carriage would be moved to the rear, and it would be necessary to wheel the piece back into position and relay it before firing again.

To bring the carriage stresses down to a reasonable value and to obtain carriage stability, a recoil system is interposed between the gun and the carriage. This acts as a cushion, allowing the gun tube, and sometimes part of the carriage, to be driven to the rear a limited controlled distance while the carriage or the remainder of the carriage, remains stationary. The energy that goes into recoil is expended then as work done by the recoiling parts in moving against the resistive force of the cushion; and there is transmitted to the carriage only that resistive force which may be very much less than the force of firing. After absorbing the recoil energy over a

convenient length, the recoil system returns the gun to battery for further firing. The recoil problem, however, is not limited to artillery carriages. Mounts for aircraft cannon, tank artillery, and self-propelled artillery must be protected from stresses due to firing, applying techniques of analysis similar to those discussed here.

The recoil system is a recent development as the history of cannon goes. It was invented in 1888, by a German engineer named Haussner, and was put to use by the French in 1897, in the famous French 75. The greatly improved rate of fire and accuracy made possible by recoil systems amounted to a revolution in artillery, and by the end of World War I all nations adopted them.

Because gun carriages are constructed to limit the recoil to a moderate length, it is necessary to determine all the circumstances of recoil in order that the forces acting at each instant may be known. The parts of the carriage then may be designed to withstand these forces and to absorb the recoil in the desired length. Since it is awkward to determine directly the circumstances of recoil when opposed by the various resistances of the recoil system (retarded recoil), the hypothetical problem of free recoil will be solved first; then the effect of the resistances will be added.

7-2 VELOCITY OF FREE RECOIL

Free recoil assumes that the gun is mounted so that it may recoil freely; that is, without any resistance. On explosion of the charge, the propellent gases act upon the whole system, including the recoiling parts, the projectile, and the propelling charge itself (the propelling charge including at any instant both the unburned and

the gaseous portions). While the projectile is in the bore, if air resistance be neglected, none of the energy of the powder gases is expended outside the system; and the momentum of the recoiling parts is equal and opposite in direction to the momentum of the projectile and propelling charge.

The assumption is made that the velocity of the center of mass of the products of combustion is half the velocity of the projectile; hence, while the projectile is in the bore, and only while it is in the bore, the following reaction exists:

$$\frac{W}{g} v_f = \left(\frac{p + 1/2\ c}{g}\right) v_p \text{ or}$$

$$v_f = \left(\frac{p + 1/2\ c}{W}\right) v_p \tag{7-1}$$

where

v_f = velocity of free recoil, ft/sec
v_p = velocity of projectile, ft/sec
W = weight of recoiling parts, lb
p = weight of projectile, lb
c = weight of charge, lb

Note that the quantity $\dfrac{p + 1/2\ c}{W}$ is a constant for a given situation; hence

$$v_f \propto v_p.$$

Since the propellent gases continue to act on the gun for a brief time after the projectile leaves the muzzle, the maximum velocity of free recoil will be greater than the maximum value given by the above equation. Based on experiments, the following empirical equation has been accepted:

$$V_f = \frac{pV + 4700c}{W} \tag{7-2}$$

where

V_f = maximum velocity of free recoil, ft/sec
V_p = muzzle velocity (instrumental), ft/sec
4700 = empirical constant representing velocity of propellent gases after projectile leaves the muzzle, ft/sec

Once the maximum velocity of free recoil is attained, the gun would continue to recoil at this velocity indefinitely, since in this hypothetical condition absolutely no resistance is offered.

Because the velocity of free recoil is directly proportional to the velocity of the projectile during the time the projectile is in the bore, it is possible to determine the relationship between the velocity, time, and distance of free recoil during this time by first obtaining such data for the projectile.

From LeDuc's equation the velocity of a projectile (not the recoiling parts) at any point in the bore is

$$v_p = f(u) = \frac{au}{b + u}, \tag{7-3}$$

where a and b are empirical constants (see Chapter 2, Part 2, Ballistics) and u = travel of projectile in bore at any instant, ft.

Figure 7-1 is a graph of (7-3). This provides a relation between velocity and distance; we want a relation between velocity and time.
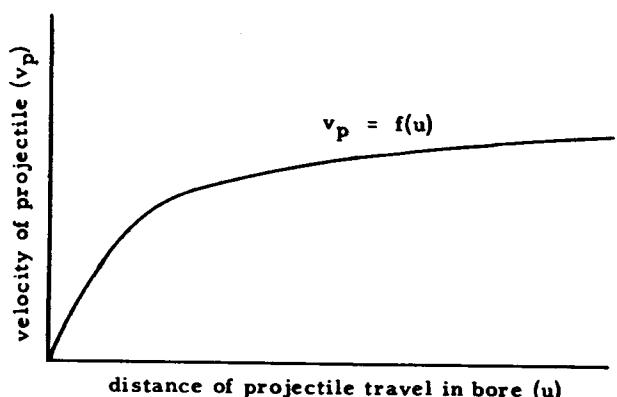
To obtain this, use is made of the relation

$$v = \frac{du}{dt}$$

which can be   n

$$v dt = du$$

or

$$dt = \frac{1}{v}\ du$$

It follows that

$$t = \int \frac{1}{v}\ du \tag{7-4}$$

From (7-3), a value of $1/v_p$ can be found for each value of u. A plot can then be made of $1/v_p$ versus u. This plot is shown in Figure 7-2.

Now, from (7-4), the integral of $1/v_p\ du$ is equal to time. Thus, for each value of u, a value of t can be found by measuring the area under the curve out to the desired value of u. This area determination can be made graphically. In order to avoid the infinite area resulting as the curve approaches the ordinate axis asymptotically, the integration is performed using some small distance, ϵ, as the lower limit of integration, rather than zero; i.e.,
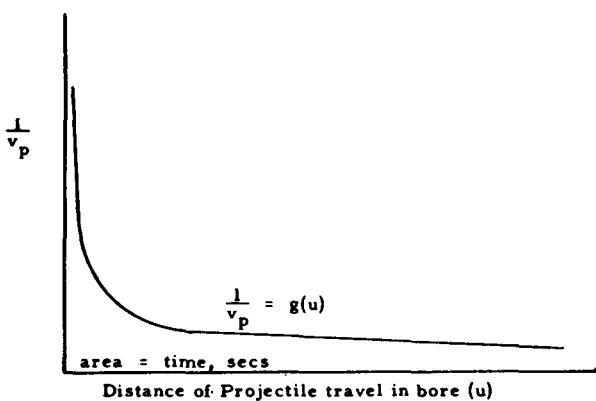
Fig. 7-2 $\frac{1}{v_p}$ versus u.
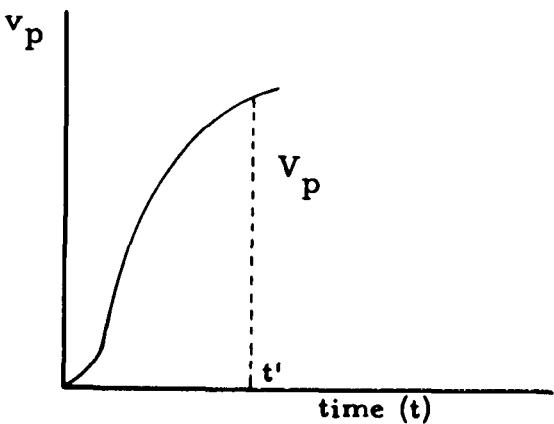
Fig. 7-3 Velocity of projectile versus time.
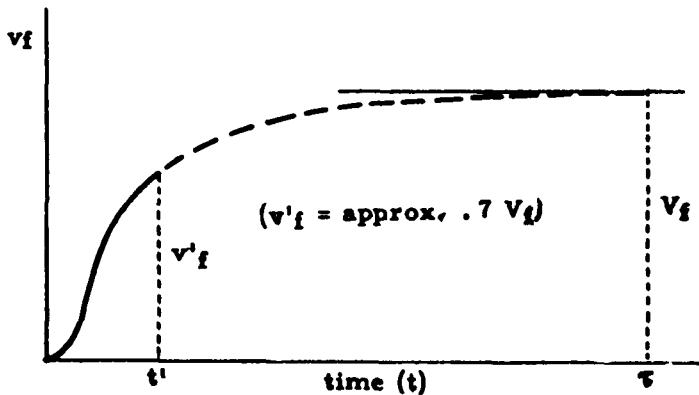
Fig. 7-4 Velocity of free recoil versus time.

$$t = \int_{\iota}^{u} \frac{1}{v_p}\, du$$

Values of v_p for each value of u are known from (7-3). Values of t for the same values of u can be found from Figure 7-2. It is now possible to plot v_p as a function of t by using these corresponding values of v_p and t. This plot is shown in Figure 7-3.

It should be noted that we have dealt with the projectile so far, not the recoiling parts. This relationship must now be adapted to the recoiling parts.

While the projectile is in the bore the velocity of free recoil, v_f, is directly proportional to the velocity of the projectile, v_p, as shown by (7-1); hence, a curve showing $v_f = f(t)$ may be plotted

out to time t', when the projectile leaves the muzzle. Specifically, if the vertical scale of Figure 7-3 be multiplied by the ratio $\dfrac{p + 1/2\, c}{W}$, then the curve for v_f out to time t' (Figure 7-4) will be obtained. At the end point, v_f will have the value v_f' corresponding to time t'. For convenience, in the following figures the velocity of the recoiling parts is plotted as positive, although it is of course opposite in direction to the velocity of the projectile. The remainder of the curve in Figure 7-4 from v_f' to V_f is constructed by finding the value of V_f from (7-2) above, and continuing the curve as a smooth one from v_f' to the point where it becomes tangent to the horizontal line at the height V_f. There is no formula, empirical or otherwise, which will yield a plot of this portion of the curve. It is done by eye.

Note that the time at which v_f becomes V_f is denoted by the symbol τ. Time τ is the total time the powder gases act on the recoiling parts. Note also, that since $\frac{du}{dt} = v$, $u = \int v\,dt$ and the area under the curve out to any time t represents the distance of free recoil up to that time.

At any instant, according to Newton's second law, a force F must be acting on the recoiling parts such that

$$F = M \frac{dv_f}{dt} \qquad (7\text{-}5)$$

where M is the mass of the recoiling parts.

7-3 RETARDED RECOIL—TOTAL RESISTANCE TO RECOIL CONSTANT

In the discussion so far all resistances to recoil have been neglected. When the gun is mounted on a carriage, the recoil brake and other forces begin to act as soon as recoil begins. The velocity of retarded recoil is consequently less at each instant than the velocity of free recoil shown by Figure 7-4. Let us assume for the purpose of this treatment a constant resistance to recoil, R, acting in opposition to the force, F, of (7-5); therefore, the net force acting on the recoiling parts will be $F - R$, and the following result is obtained:

$$F - R = M \frac{dv_r}{dt} \qquad (7\text{-}6)$$

where v_r is the velocity of retarded recoil or velocity of actual recoil. If both sides of (7-6) are integrated with respect to time the following result is obtained:

$$\int F\,dt - \int R\,dt = Mv_r \qquad (7\text{-}7)$$

since

$$\int F\,dt = Mv_f$$

from (7-5) and

$$\int R\,dt = Rt$$

since R is a constant, this equation becomes

$$Mv_f - Rt = Mv_r$$

and dividing both sides of the equation by the mass, M, the following equation results:

$$v_r = v_f - \frac{R}{M} t \qquad (7\text{-}8)$$

Note that (7-8) is a velocity equation since $\frac{R}{M}$ is a force divided by a mass yielding acceleration, which when multiplied by time t, becomes a velocity term. It can be seen that $\frac{R}{M} t$ is the velocity that would be attained in time t if a force R were acting alone on a mass M.

Areas under the v_r curve in Figure 7-5 represent the distance recoiled at the corresponding times, since the distance of retarded recoil equals the integral of v_r with respect to time $\left(u = \int_{t_0}^{t_1} v_r\,dt \right)$.

7-4 STABILITY OF MOBILE CARRIAGES

During the firing of a gun mounted on a mobile carriage there are two opposing moments. One tends to overturn the gun and the other tends to keep it on the ground. For the gun shown in Figure 7-6 the center of moments is the spade at the end of the trail, and the gun tends to pivot in a vertical plane about this point.

Carriage jump is undesirable as it interferes with rapid aiming and firing of the weapon and

is hazardous to the crew. To prevent this jump, the restoring moment due to the weight of the gun and carriage must be greater than the overturning moment due to the recoil force. This is the principal consideration which determines the allowable total resistance of the recoil system in a wheeled carriage. Artillerymen, however, are willing to accept a certain amount of jump rather than contend with the additional weight necessary to eliminate all jump.
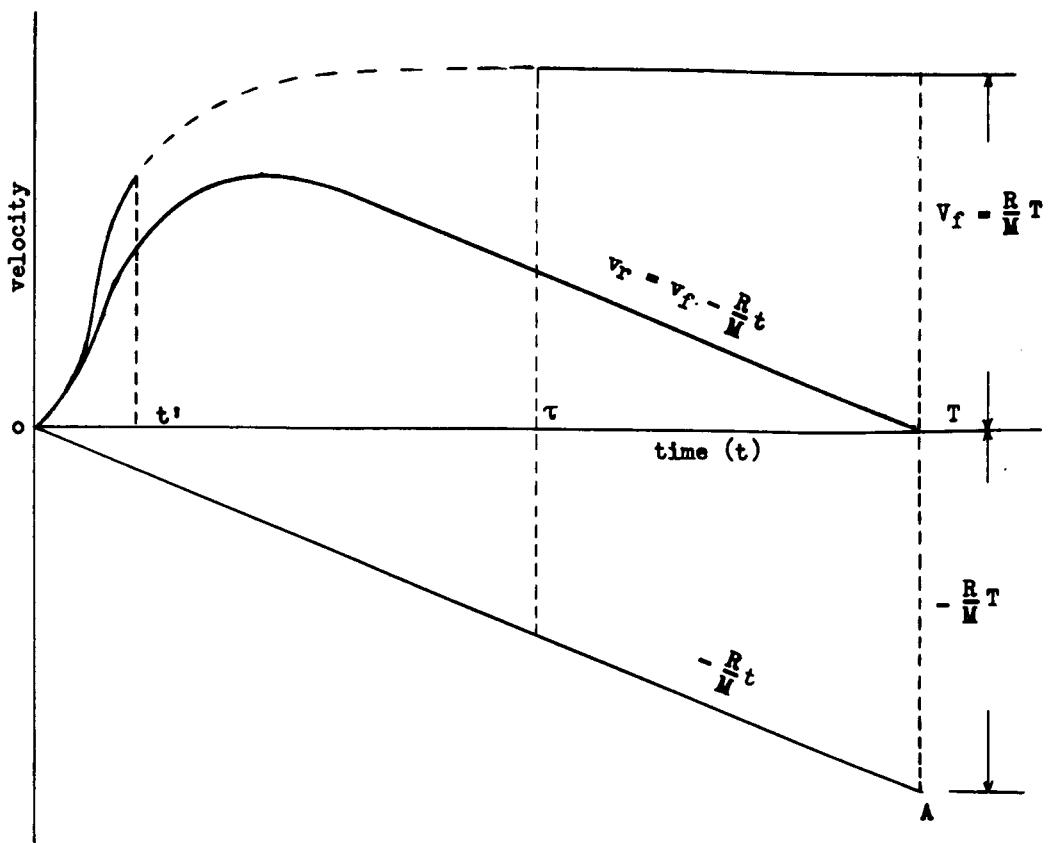
Fig. 7-5 Velocity of retarded recoil versus time.
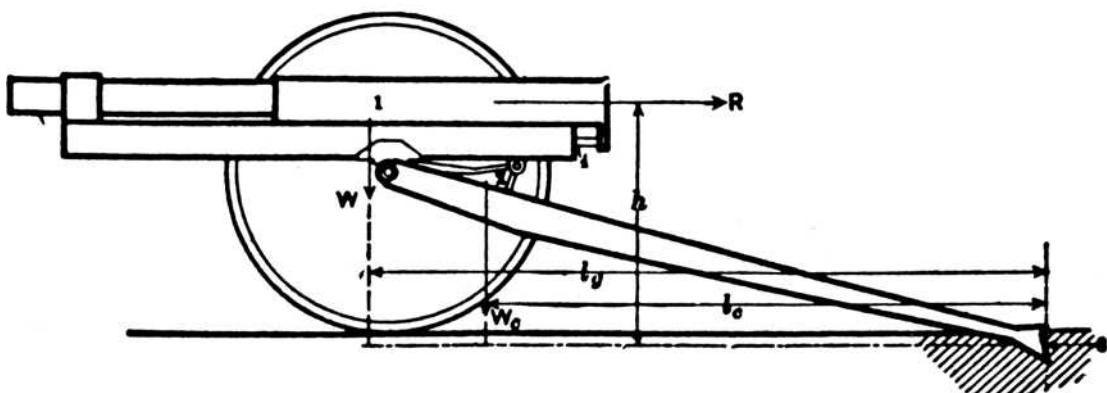
Fig. 7-6 Moments on wheeled carriage.

With reference to Figure 7-6, let

W = weight of recoiling parts acting at their center of gravity, lb

l_g = lever arm of recoiling parts when gun is in battery, ft

W_c = weight of nonrecoiling parts of carriage acting at their center of gravity, lb

l_c = lever arm of nonrecoiling parts, ft

R = total resistance to recoil, lb (acting through center of gravity of recoiling parts)

h = lever arm of R, the perpendicular distance from spade to the recoil path of the center of gravity of W, ft

The condition for stability during recoil is that the overturning moment be less than or equal to the restoring moment. Consulting Figure 7-6, the force R, which is the effect of the resistance to recoil on the carriage, multiplied by the distance h gives the overturning moment (clockwise), which must be at least balanced by restraining moments (counterclockwise) to provide stability. Therefore, in order to find out how large a value of R any given weapon can tolerate, clockwise and counterclockwise moments about the spades are equated and we solve for R_m which is the maximum allowable resistance to recoil. As the recoiling parts move rearward in recoil, all possible values of R_m may be calculated. However, ordinarily it is sufficient to calculate R_m for the in battery condition of the piece and the full recoil position. The value of R_m for the full recoil position is a smaller value than that for the in battery position which shows that a value of R small enough to prevent jump of the wheels in the early part of recoil might still cause jump toward the end of recoil as the restoring moment decreases.

In Figure 7-7 the line $R_{m1}R_{m2}$ indicates the maximum allowable values of R plotted as a function of the instantaneous distance of recoil. This $R_{m1}R_{m2}$ line is conveniently obtained by plotting R_{m1} for in battery above 0 length of recoil and R_{m2} for full recoil above L_c length of recoil, and connecting the two points. If the recoil system be designed so that R has some constant value R_c, the length of recoil will be
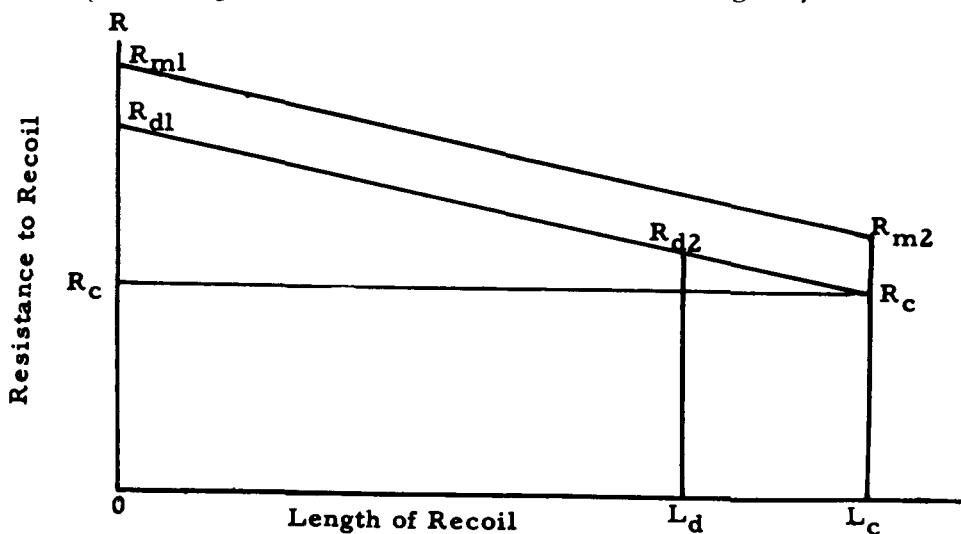
determined by the work necessary to stop the recoiling parts. This work is represented on Figure 7-7 by $\int R dL$. Thus, the area of the rectangle $R_cR_cOL_c$, represents the work necessary to stop the recoiling parts of this system. Since R_c is always less than R_m, there will be no carriage jump. The margin of stability is $R_m - R_c$ at various distances of recoil. The factor of stability is $\dfrac{R_m}{R_c}$

The length of recoil can be further shortened and stability maintained if R for the in-battery position starts at some value greater than R_c and decreases so as to be less than R_m at all points. The line R_dR_d shows such a solution. With a greater force acting on the recoiling parts, the work necessary to absorb the recoil energy can be accomplished in a shorter distance L_d. The work area $R_dOL_dR_d$ is equal to the area $R_cOL_cR_c$ since the work is the same. Thus a variable resistance to recoil allows a shorter recoil.

If the gun is stable at zero elevation then it will be even more stable when elevated since the lever arm h of the overturning moment decreases as elevation increases. This situation allows a greater value of R and thus a shorter length of recoil at high elevations.

ILLUSTRATIVE EXAMPLE:
GIVEN:

A certain howitzer weighs 3000 pounds. The weight of the recoiling parts is 1000 pounds. Their center of gravity when horizontal and in

Fig. 7-7 Resistance to recoil.

firing position is 40 inches above and 100 inches forward of the point of support of the spade. The non-recoiling parts of the carriage weigh 2000 pounds and their center of gravity is 90 inches forward of the same point.

REQUIRED:

(a) Determine the maximum value the resistance to recoil can have to insure stability both when the gun is in battery and when it has reached the end of a 40-inch recoil.

(b) If the factor of stability at full recoil is 1.5, what is the value of the constant resistance to recoil?

(c) If a constant margin of stability of 2000 pounds is maintained, by how much can the total length of recoil be shortened?

SOLUTION:

(a) With reference to Figure 7-6, let

$W = 1000$ lb
$l_g = 100$ in. (in battery)
$\quad\quad 60$ in. (in full recoil)
$W_c = 2000$ lb
$l_c = 90$ in.
$R_m = ?$
$h = 40$ in.

In battery computations:

$h \times R_m = W \times l_g + W_c \times l_c$
40 in. $R_m = 1000$ lb $\times 100$ in. $+ 2000$ lb $\times 90$ in.
$40 R_m = 100{,}000 + 180{,}000$

$$R_m = \frac{280{,}000}{40} = 7000 \text{ lb}$$

At the end of a 40 in. recoil:

$h \times R_m = W \times l_g + W_c \times l_c$
40 in. $\times R_m = 1000$ lb $\times 60$ in. $+$
$\quad\quad\quad 2000$ lb $\times 90$ in.
$40 R_m = 60{,}000 + 180{,}000$

$$R_m = \frac{240{,}000}{40} = 6000 \text{ lb}$$

(b) Plotting the values of R_m obtained from requirement (a):
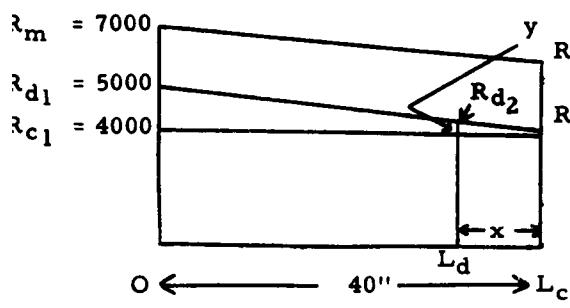
Then at maximum recoil the constant resistance to recoil (R_c) computed with a factor of stability of 1.5 is

$$1.5 = \frac{R_m}{R_c} = \frac{6000}{R_c}$$

$$R_c = \frac{6000}{1.5} = 4000 \text{ lb}$$

(c) Having established a margin of stability of 2000 pounds (see figure in (b) above), the work performed by the recoil system with a variable resistance to recoil is represented by the area of the trapezoid $O\,L_d R_{d_2} R_{d_1}$. Since the work performed must be the same as that done by a constant force then:

Area $O\,L_c R_{c_2} R_{c_1}$ = area $O\,L_d\,R_{d_2}\,R_{d_1}$

Equation (1) 4000×40

$\quad = 1/2\,[5{,}000 + (4000 + y)]\ (40 - x)$

Equation (2) $\dfrac{R_{d_1} - R_{c_1}}{y} = \dfrac{40}{x}$ or $\dfrac{1000}{y} = \dfrac{40}{x}$

$$y = \frac{1000x}{40} = 25x$$

$$4000 \times 40 = \frac{1}{2}\,[5000 + (4000 + 25x)]\,(40 - x)$$

$320{,}000 = (9000 + 25x)\,(40 - x)$
$320{,}000 = 360{,}000 + 1000x - 9000x - 25x^2$
$25x^2 + 8000x - 40{,}000 = 0$
$x^2 + 320x - 1600 = 0$

Solve for the value of x using the quadratic formula,

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-320 \pm \sqrt{102400 + 6400}}{2}$$

$$x = \frac{-320 \pm \sqrt{108800}}{2}$$

$$x = \frac{-320 \pm 330}{2} \text{ taking positive value}$$

$$x = \frac{10}{2} = 5\text{-in. recoil shortened}$$

7-5 MAJOR COMPONENTS OF A RECOIL SYSTEM

The modern recoil system has three principal parts:

(a) Recoil brake to stop recoil.

(b) Counterrecoil mechanism to return the gun to battery and to hold it there until fired.

(c) Counterrecoil buffer to reduce the shock on the carriage at end of counterrecoil.

7-6 RECOIL BRAKE

The recoil brake is a hydraulic brake and consists essentially of a piston which moves in a cylinder filled with oil. The recoil brake is attached to the weapon in either of two ways listed below. In either case, when the tube recoils, there is a relative motion between the piston and the cylinder and the operation in both cases is fundamentally the same.

In one arrangement, the cylinder is attached to the tube and moves with it during recoil and counterrecoil, while the piston is fixed to the carriage.

In the other arrangement, the piston is attached to the tube and moves with it during recoil and counterrecoil, while the cylinder is fixed to the carriage (Figure 7-8). For the purpose of subsequent discussion, this particular arrangement will be assumed.

As the propellent gases push back on the barrel the piston exerts pressure on the oil. The equal and opposite reaction to this pressure is a pressure exerted by the oil on the piston. It is the reaction force on the piston which retards the velocity of the recoiling parts. The magnitude of the oil pressure on the piston is partly determined by the orifice area, which is the total cross-sectional area of all the holes through which the oil may flow at any moment. A large orifice area will allow greater flow and thus produce less pressure; whereas a small orifice area will produce higher pressure and greater retarding force.

A later paragraph will show that the resistance to recoil depends not only on orifice area but also on other factors, including instantaneous velocity of recoil. The greater the velocity of the piston through the oil, the greater the acceleration of the oil through the orifices, and the greater the force of reaction on the piston. The arrangement shown in Figure 7-8 would produce

a varying resistance to recoil. To effect a smooth retardation of the recoiling parts the rate of liquid flow must be controlled and coordinated with other variables such as instantaneous velocity of recoil. This can be done by varying the orifice area during recoil, using a throttling device.

There are several devices for throttling the liquid flow-throttling grooves, throttling bars, throttling rods, and throttling valves. All these devices offer varying orifice area to the flow of oil such that when recoil velocity is greatest, orifice area is greatest; thus, the pressure is reasonable while the tube recoils most rapidly. As recoil velocity decreases, the restricted orifice area maintains the force of resistance to recoil.

In some artillery weapons, particularly antiaircraft, a variable length of recoil is used to permit long recoil at low elevations to improve stability, and short recoil at high elevations to prevent the breech from striking the ground or firing platform. Variable recoil can be accomplished in several ways, but generally it involves superimposing another orifice control in addition to one of the basic arrangement described in the paragraphs above.

A simple type of variable recoil mechanism is shown in Figure 7-11 in conjunction with the basic throttling rod type of recoil brake. A hollow piston slides on a control rod which has
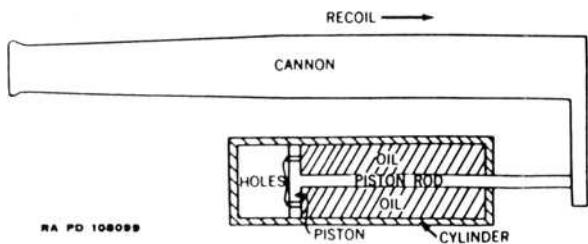
Fig. 7-8 Simple recoil brake.
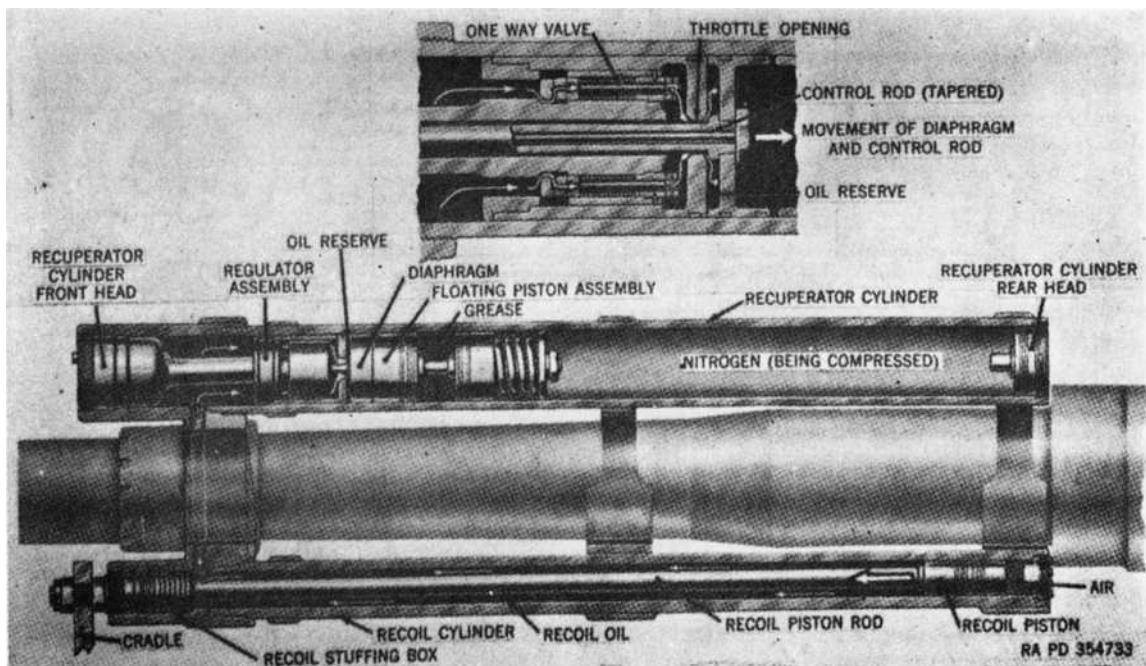
Fig. 7-9 Recoil mechanism for 105-mm howitzer, showing movement during recoil.
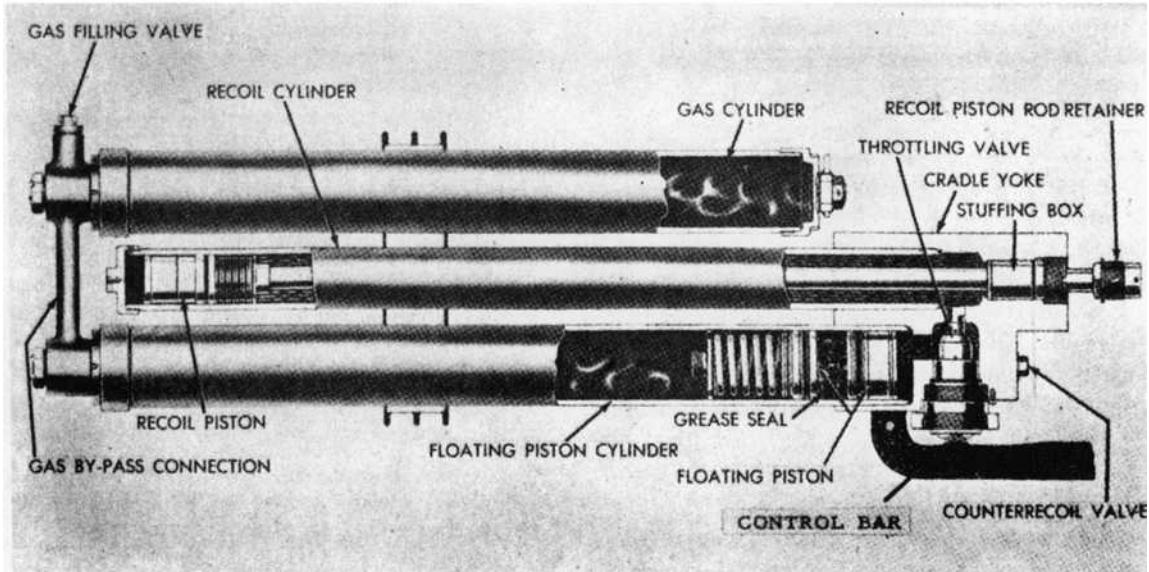
Fig. 7-10 Recoil system for 90-mm antiaircraft gun.

throttling grooves in it. The rotation of the rod is controlled by the angle of elevation of the gun through gears and cams. Maximum recoil is attained when these grooves line up with ports in the piston head, since a maximum flow of liquid is then possible. To reduce the length of recoil, the control rod is rotated, and the throttling grooves move out of line with the ports. This action reduces the orifice through which the liquid can flow, thus shortening the recoil.
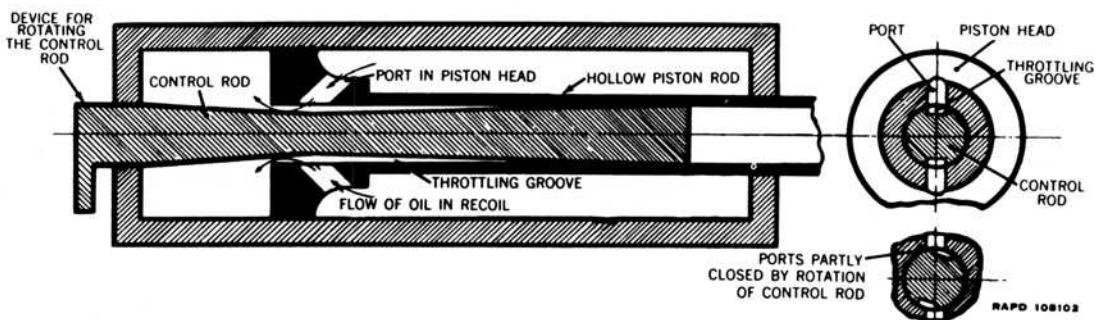
Fig. 7-11 Variable length recoil device.
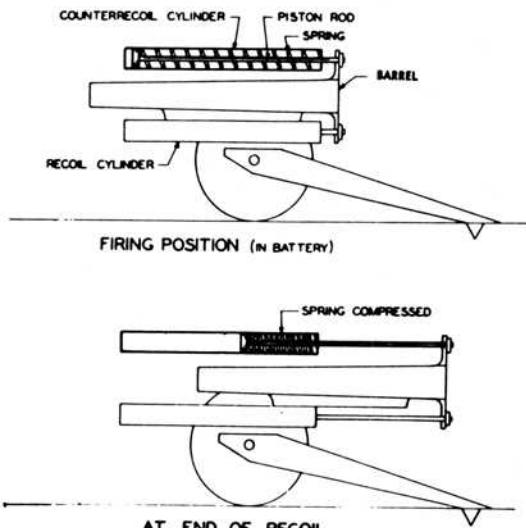
Fig. 7-12 Spring counterrecoil mechanism.
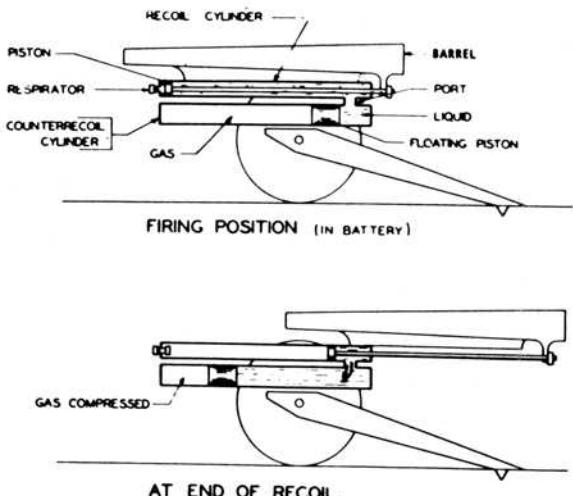
Fig. 7-13 Pneumatic counterrecoil mechanism.

7-7 COUNTERRECOIL MECHANISM

A counterrecoil mechanism is one which has the primary function of returning the barrel from its recoiled position to its firing position and holding it there until fired again. As an addi-tional function it also assists the recoil brake in stopping recoil, furnishing about 20% of the total braking force. There are two basic types of counterrecoil devices: spring, and pneumatic.

7-7.1 SPRING TYPE

In this case the entire system is known as a hydrospring recoil system. The essential parts of a spring mechanism are a spring, a cylinder, and a piston and rod (Figure 7-12).

With the barrel in battery the spring is com-pressed only enough to hold the recoiling parts in battery at all angles of elevation. When the wea-pon is fired, the barrel recoils, pulling the piston rod and further compressing the spring. At the end of recoil the spring expands and returns the barrel to firing position.

A more compact arrangement can be used where the spring is placed in the recoil brake cylinder (Figure 7-8) and expands against the brake piston. In this case the spring and the liquid occupy the same part of the recoil cylinder.

7-7.2 PNEUMATIC TYPE

In this case the entire system is known as a hydropneumatic recoil system. The essential parts of a hydropneumatic mechanism are shown in Figure 7-13.

With the gun in battery the gas, usually nitrogen, is under some initial compression to hold the recoiling parts in battery. When the weapon is fired, the liquid is forced through a throttling device and against the floating piston, which moves against the gas, compressing it further. At the end of recoil the gas expands and returns the barrel to firing position. A respirator allows air to enter the recoil cylinder during recoil and allows it to escape during counterrecoil.

7-8 COUNTERRECOIL BUFFER

A counterrecoil buffer is that part of the recoil system which controls the final movement of the recoiling parts as they come back into battery. Its purpose is to decelerate the moving parts smoothly and prevent damage by shock, yet not retard the movement to the extent that rate of fire would suffer.

A simple type of buffer is the dashpot (Figure 7-14). This consists of a tapered rod (buffer rod) which slides in and out of a cylindrical cavity, or dashpot. As the barrel recoils, the buffer rod is withdrawn from the dashpot, which then fills with liquid. During the latter part of counterrecoil, the liquid-filled dashpot rides over the buffer rod and the escape of liquid from inside the dashpot is permitted only through the narrow clearance between the rod and dashpot. As the dashpot encloses the buffer rod, the orifice for release of the liquid becomes smaller, and the motion of the piston rod and its dashpot meets with great resistance in the last few inches of counterrecoil. The barrel thus is eased into battery without jarring the carriage.

There are other types of hydraulic buffers, but they operate on the same principle of a tapered rod restricting the flow of oil to provide increased resistance toward the end of counterrecoil.

AT START OF COUNTERRECOIL

AT END OF COUNTERRECOIL
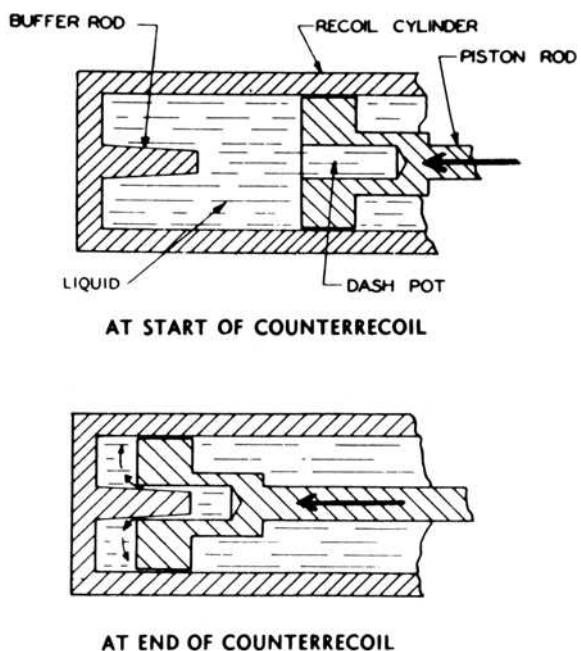
RA PD 64978

Fig. 7-14 Dashpot counterrecoil buffer.

7-9 COMPLETE RECOIL SYSTEMS

The modern recoil system, particularly hydropneumatic, is actually much more complex than indicated by the schematic figures above. The hydropneumatic system is more complex and expensive, but it has almost replaced the hydrospring system in current weapons. One notable exception to the trend toward elimination of the hydrospring system is the concentric recoil system. This finds application where space limitations are critical. A comparison follows:

(a) Hydrospring advantages
Simplicity of design
Ease of manufacture of system
Low initial cost
Rapidity of repair in the field
(b) Hydrospring disadvantages
Wide variations in serviceability of springs
High replacement rate
Bulkiness (except in concentric system described below)

Difficulty in securing required physical characteristics for springs

Weight prohibitive for large caliber mobile materiel

(Disadvantages increase with increase in caliber)

(c) Hydropneumatic advantages
Reliability of performance
Durability
Smooth action
Adjustable to slight variations

(d) Hydropneumatic disadvantages
High initial cost
Repairs require special facilities and expert mechanics
Maintenance is required while in storage

The concentric system achieves its compactness by having the gun tube act as both recoil piston rod and counterrecoil piston rod, and having the recoil brake piston, the recoil cylinder, and the counterrecoil spring mounted concentrically with the gun tube (Figure 7-15). The recoil cylinder is formed by the inside of the cradle and the outside of the gun tube enclosed by the cradle. When ready for operation the recoil cylinder is completely full of oil.

As the gun recoils, the piston compresses the counterrecoil spring and at the same time forces the recoil oil from the rear to the front of the piston. The inside diameter of the cradle becomes less as the recoil progresses, practically shutting off the flow of oil at the end of recoil. This throttling of the recoil oil and the high compression of the spring stops the rearward movement of the gun.

The compressed spring immediately starts the counterrecoil action, forcing the oil past the piston from front to rear. Near the end of counterrecoil a buffer chamber restricts the flow of oil and thus sets up a cushioning effect which permits the gun to return to battery without severe shock.

The recoil action is so well controlled that the average length of recoil of a tank gun is from 9 to 12 inches.
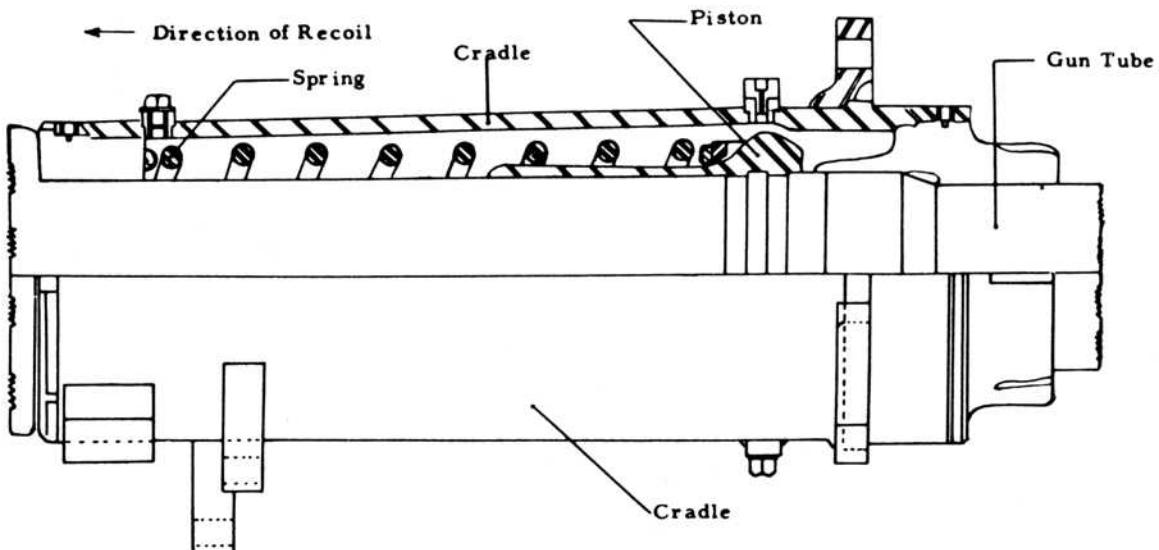

Fig. 7-15 Concentric recoil mechanism.

7-10 MUZZLE BRAKES

A muzzle brake is a device, attached to the muzzle end of a gun tube (Figure 7-16), consisting of one or more sets of baffles. These baffles deflect the escaping gases and thus by momentum transfer cause a force to act on the gun tube which mitigates the recoil force. Prior to and during World War II the Germans did extensive research into the practicability of muzzle brakes and developed many different designs. Continued research is being conducted by the United States and foreign countries.

Although a muzzle brake offers several advantages, these are offset by several practical disadvantages. While it is true that a muzzle brake may reduce the length of recoil, it still adds weight at the muzzle of the gun which puts a large torque about the gun support (i.e., trunnions) requiring the employment of equilibrators to assist in supporting the tube. If a tank turret is designed allowing only for the recoil of its gun with a muzzle brake, then failure of the muzzle brake would put the tank gun out of action. Thus, modern tank guns of the United States are not being designed for or equipped with muzzle brakes.

A muzzle brake reduces the recoil force transmitted to the mount, and also reduces obscuration of the target. After the projectile leaves the muzzle, some of the powder gases are decelerated and deflected to the sides and rear (Figure 7-17). The reaction to this decelerating force exerts a forward pull on the muzzle and thus reduces the net force which makes the gun recoil. The result is greater carriage stability, improved accuracy because of less gas turbulence affecting the projectile just beyond the muzzle, and a shorter length of recoil.

Since the baffles are positioned to deflect the blast to the sides rather than up and down, dust disturbance is minimized. The gun crew can therefore observe the target much better and maintain a higher rate of aimed fire.
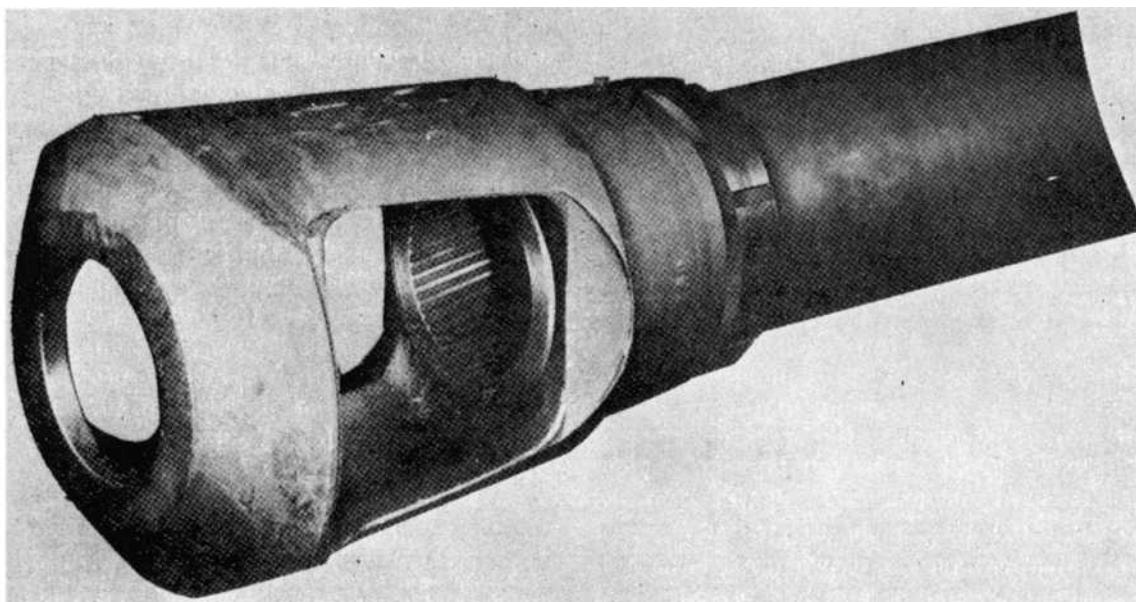

Fig. 7-16 Muzzle brake for experimental, self-propelled 155-mm gun, T80. The single baffle is approximately 85% as effective as multiple baffles, but much easier to manufacture.

A muzzle brake may be used, therefore, where it is important to have a short length of recoil, such as in a tank turret, and where obscuration is an important consideration, such as in tank and antitank guns.

The present model gun being installed in the 90-mm gun tank, M47, does not have a muzzle brake. The muzzle brake has been replaced by the diffusor (Figure 7-18). The diffusor is a hollow, straight, one piece casting, internally threaded at one end to screw onto the muzzle of the gun tube. Two holes are bored laterally through the front of the diffusor, allowing the diffusor to act as an antiobscuration device. A portion of the muzzle blast is directed to the sides, thus reducing target obscuration caused by blast cloud and dust disturbance. Since diffusors have little surface perpendicular to the axis of the tube, they have but little effect on reducing length of recoil.

7-11 TOTAL RESISTANCE TO RECOIL

The total resistance to recoil is the resultant of forces due to five devices or factors:

(a) Recoil brake. The brake furnishes the greatest part of the total resistance. This component was discussed about in Par. 7-7, and its resistance is denoted by the symbol P.

(b) Counterrecoil· mechanism. This component was discussed above in Par. 7-8, and its resistance is denoted by the symbol S.

(c) Muzzle brake. The force due to the muzzle brake does not start until the projectile leaves the muzzle, and its value varies during recoil. The symbol for this component is B. This force is lacking, of course, in guns which do not require the particular characteristics afforded by muzzle brakes.

(d) Gravity. In horizontal fire the gravity component would be zero; but as the gun is elevated to an angle α, gravity will oppose the effort of the recoil brake and will tend to increase the length of recoil. The force involved is the component of the weight of the recoiling parts which acts in the direction of recoil. This is $W \sin\alpha$, and since this component diminishes the total resistance, it is negative, $-W \sin\alpha$. If the muzzle is depressed, then α is negative and the term is positive.

(e) Friction. The force of friction contributes to the total resistance, and it is a function of W and α. The component of W which acts perpendicular to the sliding surfaces between the stationary and the recoiling parts is $W \cos\alpha$. The friction force is the product of the friction coefficient f and the weight component, or $fW \cos\alpha$.

The total resistance to recoil, in pounds, is then

$$R = P + S + B - W \sin\alpha + fW \cos\alpha. \quad (7-9)$$

It is interesting to note the tremendous amount of work that must be accomplished by a recoil system, and the importance of careful design and manufacture of every detail in the system. The total resistance to recoil for a 155-mm gun is 51,000 pounds. If the same braking force of 51,000 pounds were applied to a 3200 pound automobile going 60 mph, the automobile would stop in a distance of 7.5 feet.

7-12 SPECIAL RECOIL DEVICES

The recoil mechanisms illustrated have represented standards for design of artillery weapons for many years. Systems involving electromagnetic forces, design of twin guns linked to recoil without displacing the composite center of mass, firing during forward motion, increasing mass of recoiling parts to include components of top and bottom carriages, vacuum systems, and rigid mounts have been tested and many used in special applications.

Development work is progressing on a type of recoil device designed to reduce the maximum
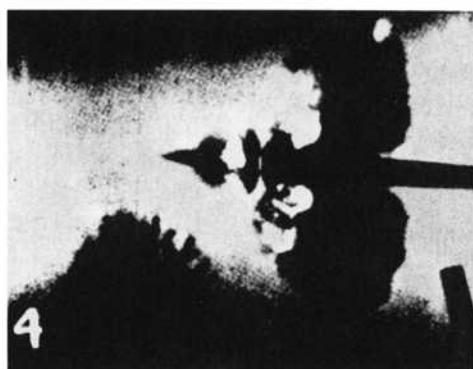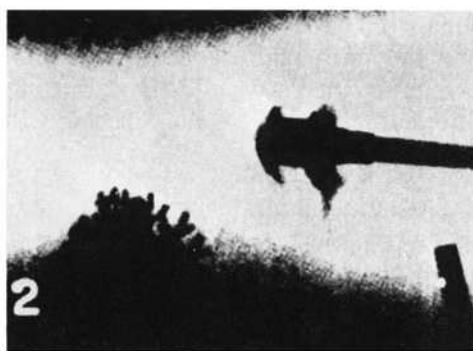
Fig. 7-17 Action of 90-mm double-baffle muzzle brake. Normally, gases are dispersed to the sides; in this case the brake was turned 90° to facilitate photography.

Fig. 7-18 90-mm gun with bore evacuator and diffusor.

forces exerted on weapon trunnions through the use of soft recoil. For weapons having a high rate of fire (usually small caliber automatic weapons) it is possible to reduce the deflection rate of the countercoil spring (make the spring soft) to the extent that the time for the full recoil cycle is greater than the time for the gun's firing cycle. That is, the gun has not been fully returned to battery at the time the succeeding round is fired. In this manner, the momentum of recoil is partially counteracted by the momentum in counterrecoil. Length of recoil is therefore shortened and trunnion reaction lessened. A problem arises in the firing of the first round, however, as there is no momentum of counterrecoil for this round. One possible solution to this problem is to simulate recoil by cranking the gun out of battery prior to firing the first round. The gun is then allowed to return toward battery freely and the first round is fired before the battery position is reached, exactly as in succeeding rounds.

It has been found that this system substantially reduces forces transmitted to weapon trunnions, a characteristic which would be most helpful in the design of weapons for use in aircraft.

The development of the carriage for the 280-mm gun represents an application of double recoil. In this arrangement two separate recoil systems are employed. One is conventional, retarding the movement of the sleigh in the cradle. The other is somewhat out of the ordinary, however, in that it provides for movement between the top and bottom carriage. This second mechanism is also a hydropneumatic system; its only departure from convention being its location between the top and bottom carriage. With double recoil, the force transmitted to the bottom carriage is reduced; therefore, elaborate preparations for emplacement of the gun are not necessary and it can be put into action quite rapidly.

REFERENCES

1 Hayes, *Elements of Ordnance,* New York: John Wiley and Sons, Inc., 1938, pp. 74-77, 241-283.

2 Dept of the Army Technical Manual, TM 9-2305, *Fundamentals of Artillery Weapons,* Washington, U.S. Government Printing Office, 1948, pp. 42-57.

CHAPTER 8

GUN MOUNTS AND MISSILE LAUNCHERS

8-1 GENERAL

A mount or carriage is an assembly which supports a weapon in firing and traveling. A missile launcher is a device which furnishes stable support for a missile or rocket, may give it initial orientation and guidance, and which may support it in travel. In this chapter the general aspects of gun mounts and missile launchers will be discussed, and a method for analyzing stresses in a structure of this type will be presented.

8-2 GUN MOUNTS

The names and short descriptions of components of gun mounts are given here. Refer to Figures 8-1 and 8-2 for their location on a typical carriage. For detailed pictures and description of operation of these components the reader is referred to Department of Army Technical Manual TM 9-2305, *Fundamentals of Artillery Weapons*.

The main barrel supporting members on a carriage are: the sleigh, cradle, top carriage, and bottom carriage. Depending upon the design of the carriage, certain of these components may or may not be present.

(a) Sleigh. The sleigh is that part of a carriage which forms the immediate support of the barrel. The sleigh recoils with the barrel on the cradle and, in many of our weapons, houses the recoil mechanism.

(b) Cradle. The cradle is that part of the carriage which supports the barrel and sleigh. Where no sleigh is used, the cradle houses the recoil mechanism. In general, the cradle is a U-shaped trough which has slides or rails on paths or guideways along which the gun recoils and counterrecoils.

(c) Top carriage. The top carriage supports the cradle in its trunnion bearings and carries the elevating mechanism. It moves with the cradle in horizontal traverse but not in changes of elevation. When the weapon is traversed, the top carriage rotates horizontally on the axle or bottom carriage.

(d) Bottom carriage. The bottom carriage is that part of the carriage assembly which supports the top carriage and has, attached to it, portions of the mechanism for rotating the top carriage in traverse.

(e) Elevating mechanisms. An elevating mechanism consists of devices for elevating or depressing the weapon and holding it at the desired angle while being fired. The final motion is generally applied through an elevating rack attached to the cradle and an elevating pinion attached to the top carriage. Whenever a rack and pinion are used, a worm and worm wheel are usually placed in the gear train to make the system irreversible and to hold the gun at the elevation set.

(f) Traversing mechanisms. A traversing mechanism is a device for making lateral changes in the direction of the barrel. The moving parts may consist of only the barrel and the upper part of the carriage; or in some cases, the moving parts may consist of the entire barrel and carriage except the axle.

(g) Equilibrators. To permit higher angles of elevation in artillery weapons, the horizontal axis about which the barrel revolves for elevation is located well to the rear of the center of gravity of the barrel. The barrel thus is unbalanced and tends to tip forward. An equilibrator is a device which overcomes this unbalanced weight and keeps the cannon in balance at all angles of elevation so that it may be elevated and depressed easily by hand (Figure 8-3).
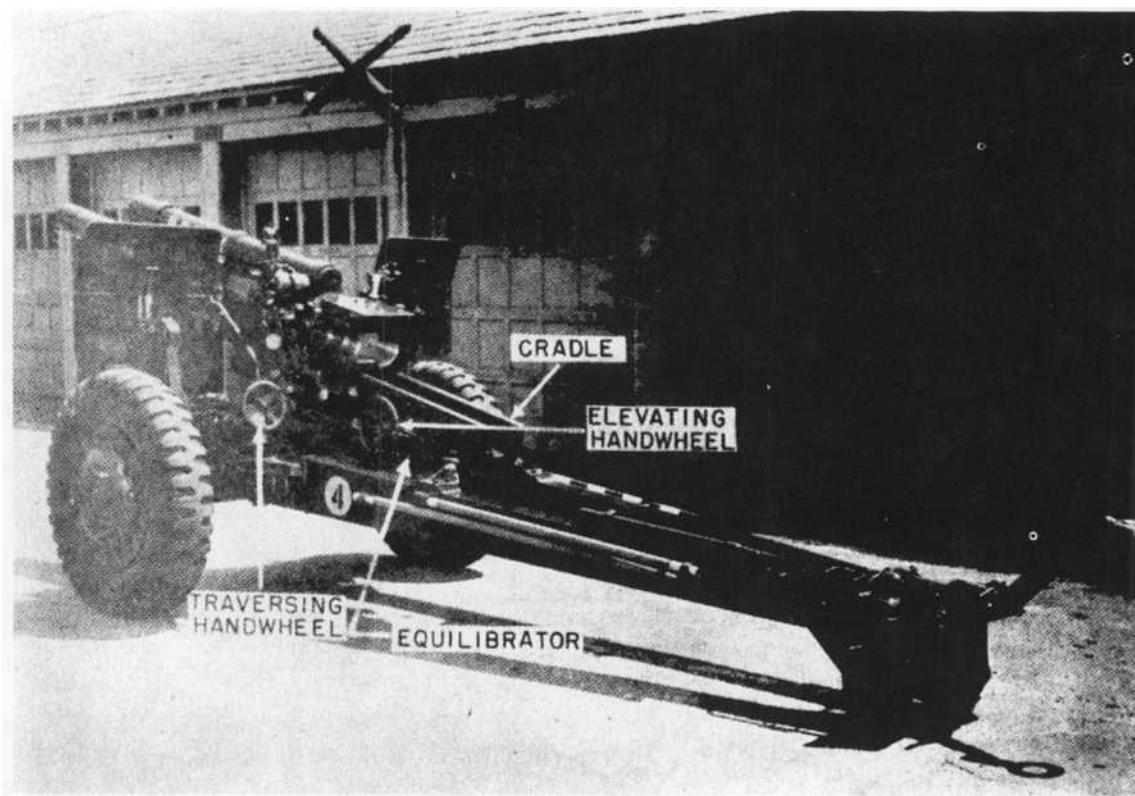
Fig. 8-1   105-mm howitzer, left rear view.
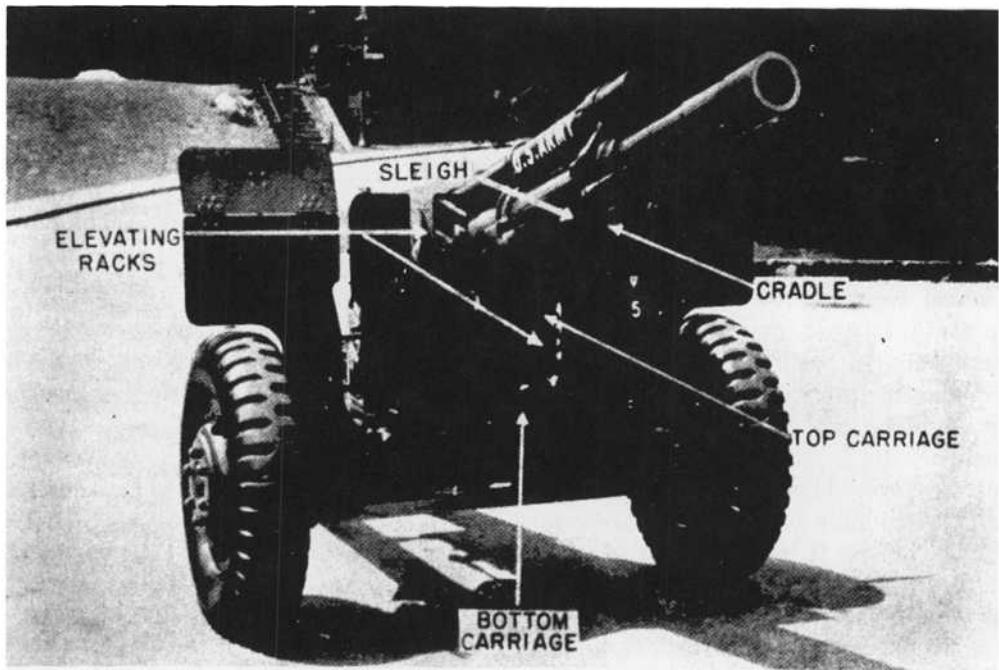

Fig. 8-2   105-mm howitzer, right front view.
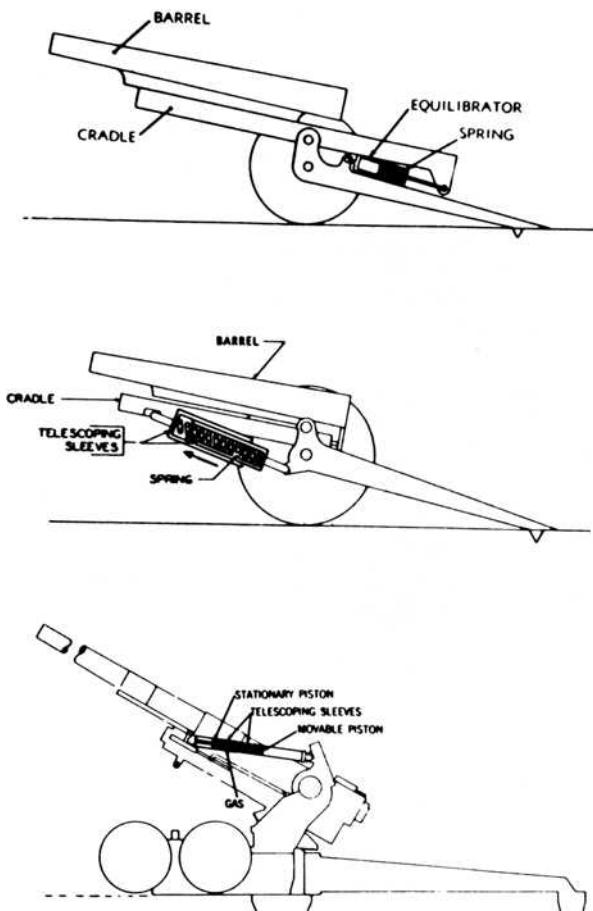
Fig. 8-3 Applications of equilibrators.

Fig. 8-4 Equalizer.

(h) Bogies. A bogie is essentially a cart which is used with certain artillery weapons for the purpose of supporting the weapon during transport. When the weapon is placed in the firing position, the bogie is either removed or so adjusted that it no longer supports the weight of the weapon, although some weapons may be fired from the bogies in emergencies.
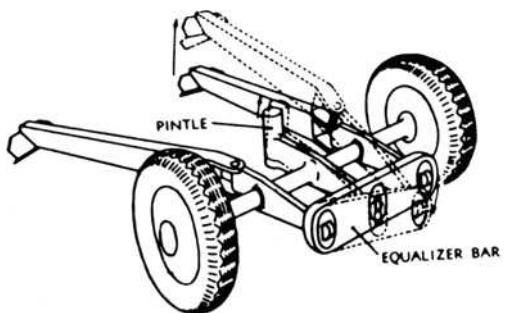
(i) Equalizers. An equalizer is a mechanical device which permits the four points of contact with the ground, the two wheels and the two trail ends, to be in different planes. It compensates for irregularity of the terrain, so that the weight of the weapon and the shock of firing are transmitted to the ground through all of the four points. Equalizers are required only on those split trail carriages which, when emplaced, rest on two wheels (or two firing segments) and on the two trail ends.

Figure 8-4 shows an equalizer where an equalizer bar, fixed to an extension of the pintle, rotates in a plane parallel to the axle. By moving the trails, the position of the equalizer bar is controlled through equalizer arms which rotate about the axle.

Some weapons which are directed by remote control equipment (e.g., antiaircraft weapons) must be accurately levelled so that they will traverse through true horizontal angles. For this purpose a levelling mechanism (e.g., levelling jacks) is used.

8-3   MISSILE LAUNCHING TECHNIQUES

Missile launchers perform some of the same functions as do artillery weapons. They provide static support for the missile and in some cases its initial orientation and guidance. The launching of guided missiles on a precise trajectory is not usually of paramount importance, as changes to the trajectory can be made after launch.

In the case of free rockets, however, since no guidance is provided after launch, the launcher must release the rocket so that it will follow a desired ballistic trajectory to the target.

Generally, missiles used in the U.S. Army employ one of three launching techniques: (1) launching from rail launchers; (2) launching from zero-length launchers; and (3) vertical launchings.
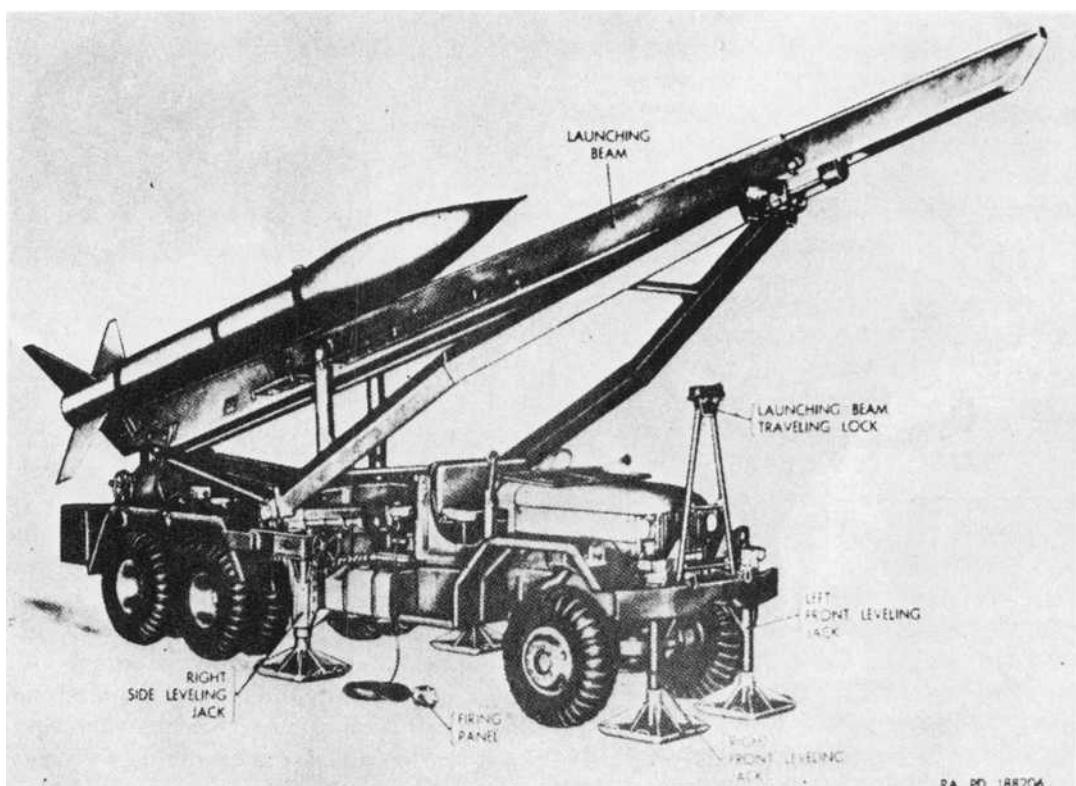
Fig. 8-5   Rail-type missile launcher.

Fig. 8-6   Dart missile on zero-length launcher.

8-3.1 RAIL LAUNCHERS

As the most common type in use by the Army, they consist of a structure supporting a set of helical or linear rails which supports the missile during launch. These launchers are of varying lengths, some being shorter than the missile being launched; others considerably longer (Figure 8-5). For free rockets, launchers must be of greater length than for guided missiles, so that the rocket is constrained for a longer proportion of the boost phase of motor burning.

The larger this proportion, the less will be the deviation from the desired trajectory. For a relatively small proportion, if the booster burns for a relatively long time after launch, any small misalignment of the boost thrust vector may cause serious deviations from the desired trajectory.

One problem which arises in the use of rail type launchers is tip-off. This refers to the angular momentum the missile acquires if its front supports leave the rail before its rear supports. Gravity acting on the forward portion of the missile will cause its nose to drop before separation of the rear supports from the rail. Tip-off can be avoided by using separate rails for front and rear supports so that both leave the rails simultaneously.

Rail launchers are light and simple in design, and can be mobile or fixed. They can serve as a transporting device for the missile when they are mobile, and can support the missile for fueling and launching.

8-3.2 ZERO-LENGTH LAUNCHERS

This launcher (see Figure 8-6) releases the missile as soon as motion relative to the launcher begins. They do not control the flight path of the missile, but do determine initial orientation. This launcher is not used to any great extent by the Army, a notable exception being the Dart anti-tank missile.

In order for zero-length launching to be successful, the guidance system must have the capability of immediate control of the missile after launch. The thrust unit must be carefully aligned so that the line of action of the thrust vector passes through the center of gravity of the missile. Otherwise, a pitch angle may be introduced which will cause the missile to fly into the ground before guidance becomes effective.

Zero-length launchers are extremely simple, small, light, and potentially mobile. Their use will probably be limited, however, because of inherent disadvantages indicated above.

8-3.3 VERTICAL LAUNCHINGS

This launcher (see Figure 8-7) is used for most ballistic missiles. The missile is set on end, sometimes supported on its own fins, for launch. Ballistic missiles are usually very large and heavy and a rail type launcher for these missiles would itself be unduly heavy, because of the necessity of great structural strength. Further, ballistic missiles are launched vertically in order that they may operate outside of the sensible atmosphere over most of their trajectory. Since thrust is greater in thin air than in the dense air near the surface, it is advantageous that such missiles reach rarefied atmosphere as soon as possible. The quickest path out of the sensible atmosphere is straight up. Highly specialized handling equipment is required to place the missile in the launch position. Ofter other special equipment is required to fuel and service the missile after it has been placed in the vertical position (i.e., liquid fueled rockets). These disadvantages are accepted, however, in order to gain the advantages of vertical launch.
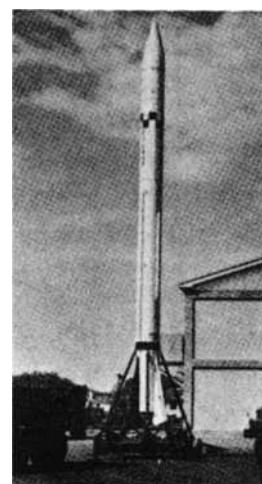
Fig. 8-7 Example of vertical launching.

8-4   STRESSES IN MOBILE GUN CARRIAGES

The problem of the designer consists of providing adequate strength for all parts without exceeding maximum limits for weight and size. In addition, he must satisfy other requirements such as those for stability, ease of operation, mobility, and convenience of maintenance and repair.

The computation of stresses hinges on analysis of the forces acting on the various parts. If certain forces are known others may be computed by resolving the forces into components and taking moments about convenient axes.

To illustrate the method of computing the stresses which occur in the various parts of a mobile carriage an example is worked out using the 105-mm howitzer, M2, and its carriage. The principles embodied in this analysis can be applied to any structure of this type. Other carriages and launchers can be analyzed using the techniques described in this paragraph. An
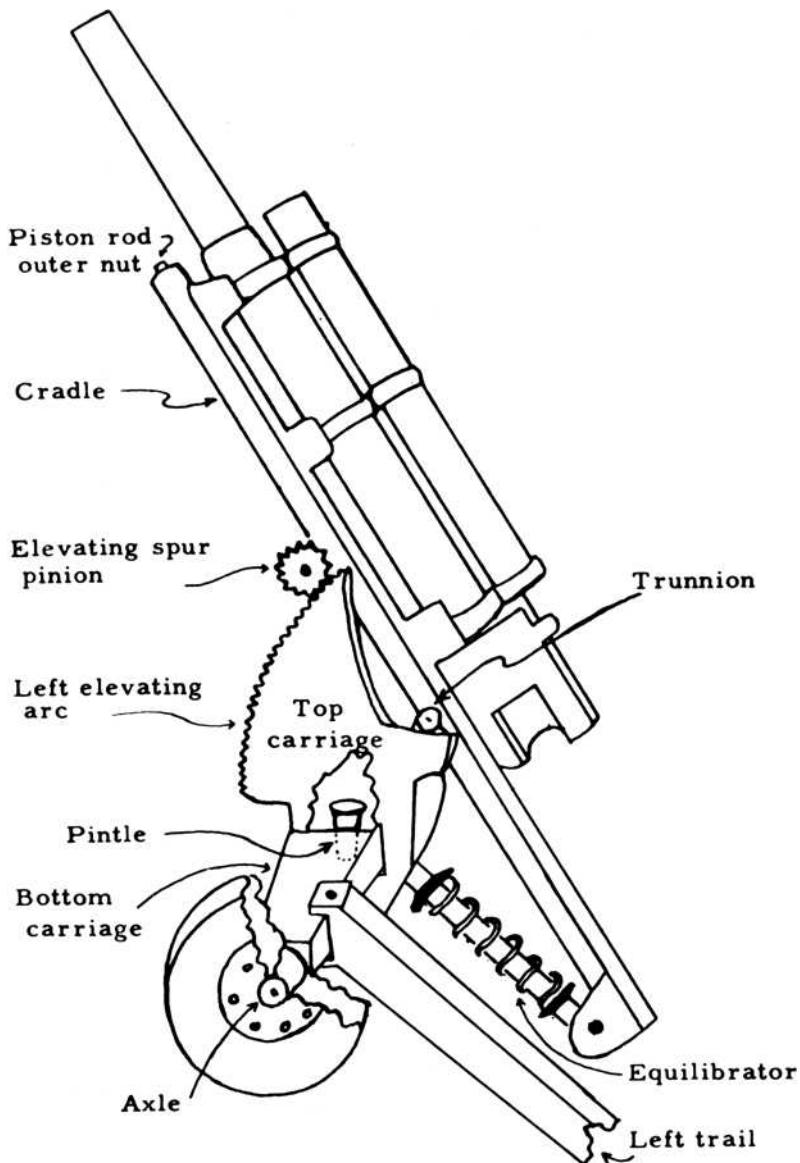
Fig. 8-8   105-mm howitzer, M2.

appreciation of the engineering involved in armament equipment can best be gained by doing some of the pick and shovel calculations.

To cover fully the critical conditions for this howitzer, calculations should be made for combinations of maximum and minimum elevations with maximum and minimum traverses, both while the piece is in and out of battery. To illustrate the computation of one set of these data, an analysis is shown with the piece out of battery (just as the piece comes to rest after recoiling 42 in.) at 0° traverse and 65° elevation.

The work on the following pages is for the most part from actual data used in the design of the 105-mm howitzer. It is modified in some particulars to suit the needs of this presentation. In one or two instances the location of the center of gravity has been assumed.

The analysis will start with the recoiling parts, and work down through the various parts to the ground, in each case evaluating the forces acting *on* the part.

The following general data are given for the 105-mm howitzer:

muzzle velocity, H.E. shell, charge 7 = 1550 ft/sec
weight of projectile = 33.0 lb
weight of powder charge = 2.8 lb
travel of projectile in bore = 6.8 ft
area of bore = 12.65 sq in.
chamber capacity = 153.8 cu in.
maximum range = 12,200 yd
weight of piece (approx.) = 4300 lb
weight of recoiling parts = 1525 lb
elevation = −5° to +65°
traverse = 22° 30′ right, 22° 30′ left
recoil (normal) = 42 in.
trail spread = 23°

8-4.1   FORCES ACTING ON RECOILING PARTS

The recoiling parts are indicated schematically by the outline in Figure 8-9. The forces acting on these parts are indicated by the arrows.

Given:
  W_r, wt of recoiling parts = 1525 lb
  W_r sin 65° = 1380 lb
  W_r cos 65° = 645 lb
  f, coefficient of friction = .15
  A, piston pull due to recoil system = 12,600 lb

Note that the center of gravity of W_r is not on the axis of the bore. The other portions of the recoiling parts such as the sleigh and piston are not shown in this schematic sketch.

Find:
  C, the force exerted by the cradle on the forward part of the recoiling parts, and
  D, the force exerted by the cradle on the rear part of the recoiling parts.

Even though the gun is considered just as it reaches the end of recoil, there is a net force acting and therefore there is a value of acceleration. In order that this may be analyzed as a static system, a hypothetical force (d'Alembert force) equal and opposite to the actual net force acting is added at the center of gravity. This force is indicated as

$M \dfrac{d^2x}{dt^2}$. Now the solution may be based on summation of forces and moments.
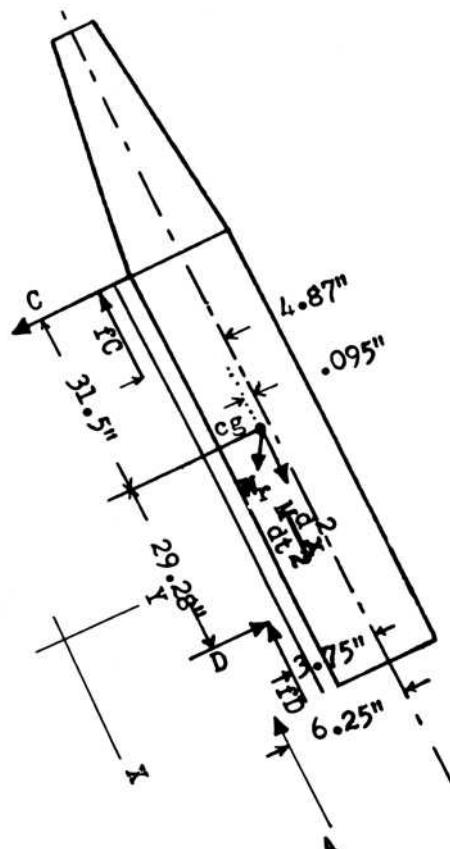
Fig. 8-9   Forces on recoiling parts.
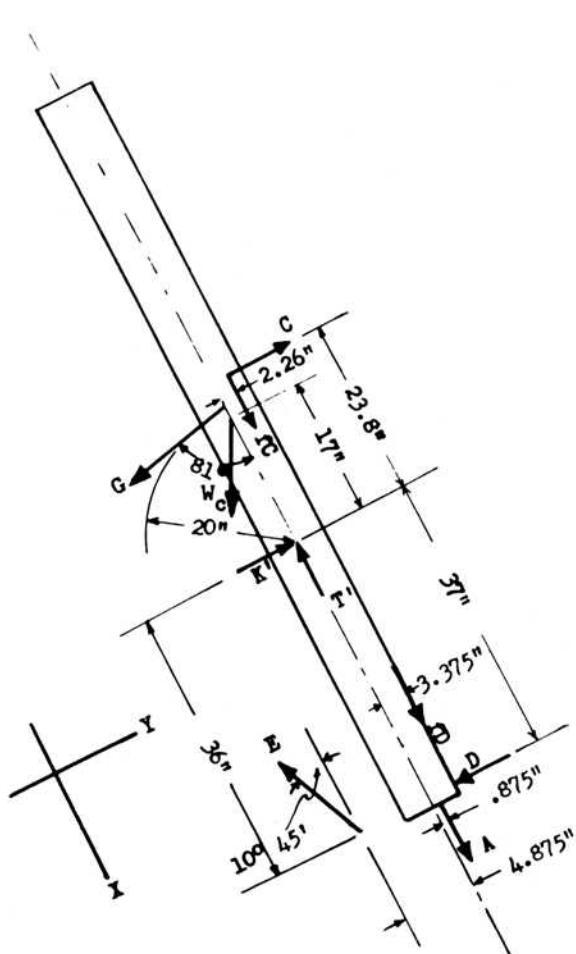
Fig. 8-10 Forces on cradle.

(1) $\Sigma F_y = -W_r \cos 65° - C + D = 0$

(2) $\Sigma F_x = W_r \sin 65° - fC - fD - A$

$$+ M\frac{d^2x}{dt^2} = 0$$

(3) $\Sigma M_{cg} = fC \times 4.775 + fD \times 3.655$

$$- 31.5C - 29.28D + 6.155A = 0$$

Since there are only two unknowns, only two equations are needed. In order to avoid being involved with the $M\frac{d^2x}{dt^2}$ term, equation (2) can be dropped.

(1) $-645 - C + D = 0$

(3) $.716C + .548D - 31.5C - 29.28D$

$$+ 77,500 = 0$$

$$- 30.784C - 28.732D + 77,500 = 0$$

$$C + .933D = 2518$$

(1) $\dfrac{-C + D = 645}{1.933D = 3163}$
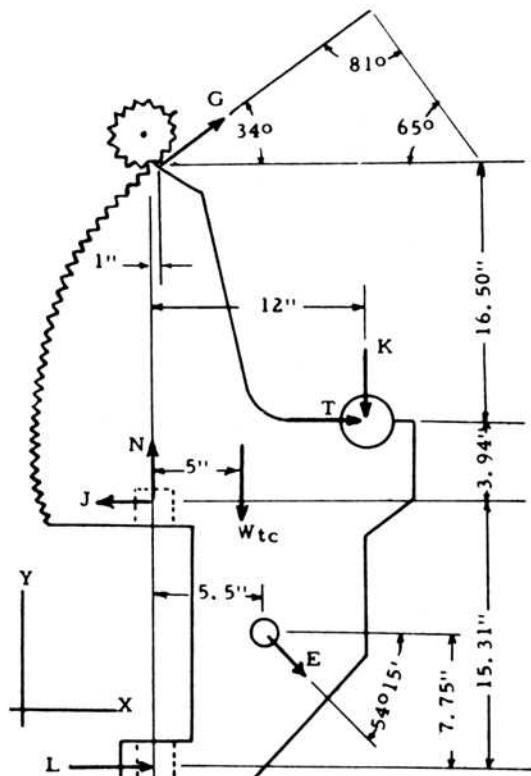
Fig. 8-11 Forces on top carriage.

(1) $-645 - C + 1640 = 0$

$D = 1640$ lb (approx)

$C = 990$ lb (approx)

8-4.2 FORCES ACTING ON THE CRADLE

Refer to Figure 8-10.

GIVEN:

W_c, wt of cradle = 460 lb

$W_c \sin 65° = 416$ lb

$W_c \cos 65° = 195$ lb

E, equilibrator pull = 740 lb

$E \sin 10° 45' = 137$ lb

$E \cos 10° 45' = 725$ lb

$A = 12,600$ lb

$C = 990$ lb

$D = 1640$ lb

FIND:

G, the force exerted on the elevating spur gear. Note that in this case the elevating rack is part of the top carriage.

K' and T', components of the force on the trunnions.

Again force and moment equations can be written and solved simultaneously. The results

are given below.

$$G = 5080 \text{ lb}$$
$$K' = 6000 \text{ lb}$$
$$T' = 13,480 \text{ lb}$$ resultant $= 14,760 \text{ lb}$

8-4.3 FORCES ACTING ON TOP CARRIAGE

Refer to Figure 8-11.

GIVEN:

$$G = 5080 \text{ lb}$$
$$G \sin 34° = 2840 \text{ lb}$$
$$G \cos 34° = 4210 \text{ lb}$$
$$T = T' \cos 65° - K' \sin 65° = 260 \text{ lb}$$
$$K = T' \sin 65° + K' \cos 65° = 14,750 \text{ lb}$$
$$E = 740 \text{ lb}$$
$$E \sin 54° 15' = 600 \text{ lb}$$
$$E \cos 54° 15' = 433 \text{ lb}$$
$$W_{tc}, \text{ wt of top carriage} = 172 \text{ lb}$$

FIND:

J, N, and L, the forces exerted by the bottom carriage through the pintle.

Again force and moment equations can be written and solved simultaneously. The results are given below.

$$J = 22,000 \text{ lb}$$
$$N = 12,630 \text{ lb}$$
$$L = 17,000 \text{ lb}$$

8-4.4 FORCES ACTING ON BOTTOM CARRIAGE

Refer to Figure 8-12.

GIVEN:

W_{bc}, wt of bottom carriage $= 2143 \text{ lb}$
$$J = 22,000 \text{ lb}$$
$$N = 12,630 \text{ lb}$$ forces on the pintle.
$$L = 17,000 \text{ lb}$$

FIND:

H and V, the forces on each spade.

(1) $\Sigma F_y = -W_{bc} - N + 2Q + 2V = 0$
(2) $\Sigma F_x = J - L - 2H = 0$
(3) $\Sigma M_Q = W_{bc} \times 24 + J \times 34.06 - L$
$\qquad \times 18.75 + N \times 4.75 + 2H \times 3$
$\qquad - 2V \times 118 = 0$
(2) $22,000 - 17,000 - 2H = 0$
(3) $51,400 + 749,000 - 319,000 + 60,000$
$\qquad\qquad\qquad + 15,000 - 236V = 0$
$\qquad 236V = 556,400$
(2) $H = 2500 \text{ lb}$
(3) $V = 2360 \text{ lb}$
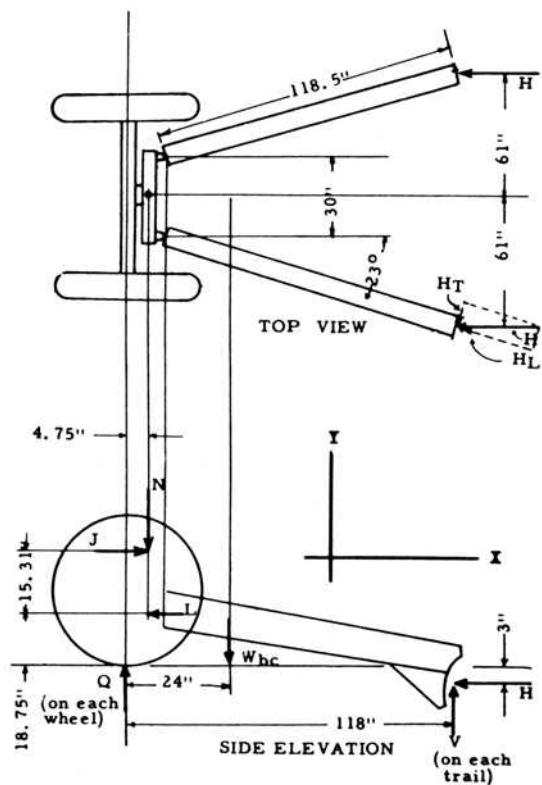
Fig. 8-12 Forces on bottom carriage.
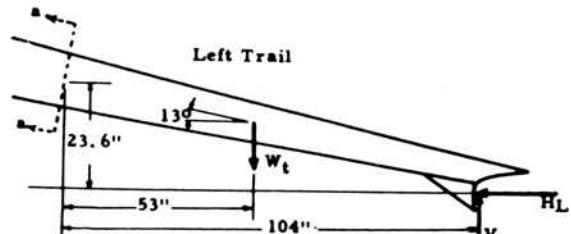
Fig. 8-13 Forces on trail.

8-4.5 FORCES ACTING ON EACH TRAIL

Refer to Figure 8-13.

GIVEN:

$$H_L = H \cos 23° = 2300 \text{ lb}$$
$$H_T = H \sin 23° = 980 \text{ lb}$$
$$V = 2360 \text{ lb}$$
W_t, wt of trail to the right of section a-$a = 250 \text{ lb}$
$$\sin 13° = .225$$
$$\cos 13° = .974$$
metal area a-$a = 4 \text{ sq in.}$

FIND:

Maximum stress in section a-a (Figure 8-14).

Y
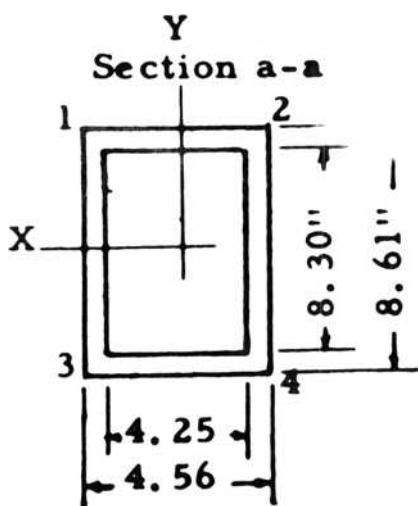
Section a-a

Fig. 8-14 Cross section of trail.

In the solution of this problem the trail is considered as a simple beam with forces acting upon it as shown Each of the forces H_L, H_T, V, and W_t cause a bending in section a-a creating a stress of compression in one half of the trail and tension in the other. The stress due to bending, may be found by multiplying the bending moment, M, by the distance from the neutral axis to the fiber in question, C, and dividing by the moment of inertia, I.

$$S = \frac{Mc}{I}$$

The maximum stress will exist where c is a maximum, i.e., in the surface farthest from the neutral axis.

The moment of inertia of a rectangle may be obtained by using the following formula:

$$I = \frac{b\,h^3}{12}$$

About the x-axis we have

$$I_x = \frac{4.56\,(8.61)^3 - 4.25\,(8.3)^3}{12} = 40.43 \text{ in.}^4$$

and about the y-axis

$$I_y = \frac{8.61\,(4.56)^3 - 8.3\,(4.25)^3}{12} = 15.05 \text{ in.}^4$$

The bending moment (M_x) about the x-axis at section a-a is obtained:

$$M_x = -V \times 104 + H_L \times 23.6 + W_t \times 53$$
$$= -245,000 + 54,300 + 13,300$$
$$= -177,000 \text{ in.-lb}$$

The maximum stress due to M_x occurs at the surfaces 1-2 and 3-4.
Along these surfaces

$$S = \frac{M_x c}{I_x} = \frac{177,000 \times 4.31}{40.43} = 18,900 \text{ psi,}$$

compression along surface 1-2 and tension along surface 3-4.

The bending moment (M_y) about the y-axis at section a-a due to H_T is:

$$M_y = H_T \times \frac{104}{\cos 13^\circ} = 980 \times \frac{104}{.974}$$
$$= 105,000 \text{ in.-lb}$$

The maximum stress due to M_y occurs at the surfaces 1-3 and 2-4.
Along these surfaces

$$S = \frac{M_y c}{I_y} = \frac{105,000 \times 2.28}{15.06} = 15,900 \text{ psi,}$$

compression along surface 1-3 and tension along surface 2-4.

It is apparent that, due to the bending moments, the maximum compressive stress will be at corner 1 ($18,900 + 15,900 = 34,800$ psi), and the maximum tensile stress will be at corner 4 (34,800 psi)

The three forces H_L, V, and W_t have components causing a direct stress in the trail. This stress must be determined and added to the stress due to bending.

The direct force acting along the trail is

$$-H_L \cos 13^\circ - V \sin 13^\circ + W_t \sin 13^\circ$$
$$= -2240 - 531 + 56 = -2715 \text{ lb,}$$

and the stress is

$$\frac{-2715}{4 \text{ sq in.}} = -680 \text{ psi (comp)}$$

The combined stress is the bending stress plus the direct stress. At corner 1 the stress is

$$-34,800 - 680 = -35,480 \text{ psi (comp)}$$

and at corner 4

$$+34,800 - 680 = +34,120 \text{ psi (tension)}.$$

Actual stress conditions in the trail will not be as great as the value found above, due to the

fact that the ground into which the spades are buried has a certain amount of resilience, thus lessening the stresses calculated.

The trail is constructed of low-alloy steel plate which has a tensile strength of 100,000 psi and an elastic limit of 50,000 psi

$$\text{Factor of safety} = \frac{50,000}{35,480}$$

$$= 1.41 \text{ based on elastic limit.}$$

REFERENCES

1 Hausman and Slack, *Physics,* New York: D. Van Nostrand Co., Inc., Third edition, 1948, pp. 140-158, 183-186.

2 Hayes, *Elements of Ordnance,* New York: John Wiley and Sons, Inc., 1938, pp. 284-370.

3 Higdon and Stiles, *Engineering Mechanics,* New York: Prentice Hall Inc., Second edition, 1955, pp. 92-125, 169-190, 209-240.

4 Merrill, Goldberg, Helmholz, *Principles of Guided Missile Design; Operations Research, Armament, Launching,* Princeton, New Jersey: D. Van Nostrand Co., Inc., 1956, pp. 373-386, 405-414.

5 Department of the Army Technical Manual, TM9-2305, *Fundamentals of Artillery Weapons,* Washington, U.S. Government Printing Office, 1948, pp. 57-130.

CHAPTER 9

SMALL ARMS AND RECOILLESS RIFLES

9-1 HISTORY OF SMALL ARMS

9-1.1 DEVELOPMENT OF THE MILITARY RIFLE

The earliest missile used by primitive man probably was a stone, first thrown by hand and later by use of a sling. Piercing missiles such as the javelin and spear were developed in very ancient times. The simple bow, the first weapon to discharge a piercing missile, came into use almost as early as the sling and remained of military importance until the eighteenth century. Among the developed forms of this weapon was the famous, powerful, English longbow, which was in service until 1590.

The first known written reference to a formula for gunpowder dates from about the year 1250, and firearms probably came into being about 1300. By the end of that century the earliest hand firearm (called the hand cannon) appeared, derived from the early crude cannon. This inaccurate weapon of little military significance was mainly used for its terror value, because of the sound of its explosion, the flash of fire, and the volume of dense smoke emitted.

Most of the major improvements in small arms before the 1800's were concerned with better methods of igniting the powder charge. The serpentine lock, which made its appearance about 1450, represents the first improvement over the hand cannon. The idea of the trigger was born. A further developed version of this idea, the matchlock, appeared about 1470. Simple in construction and not difficult to use when conditions were favorable (no rain), it remained in

service for about two hundred years. The disadvantages of this ignition system, foremost of which was the difficulty of keeping the match burning, and the slow method of preparing for firing, led to the development of the wheellock, about 1510, in Nuremberg, Germany. This system provided a spring-driven, serrated wheel which revolved against a piece of iron pyrites held by the cock, producing a shower of sparks to ignite the priming powder. There was no burning ember to be put out by the rain or to betray the shooter's presence, and the weapon could be fired from horseback and carried in a holster ready for use.

Although the wheellock eliminated the objectionable match, its high cost and the general unreliability of the weapon brought about the development of the snaphance lock, the forerunner of the true flintlock (1630) which was to serve as a standard military arm for 200 years and more. Serving the American pioneer and Revolutionary War soldier, the flintlock (Figure 9-1) did not disappear completely as a military weapon until after the close of the Civil War, when the percussion system of ignition came into general use.

The advantages of rifling were known about the time of the wheellock, and rifling systems had been developed long before it was practicable to adopt rifling in military weapons. The difficulty was in devising a projectile which could be readily passed down the bore and expand into the rifling when fired. The invention


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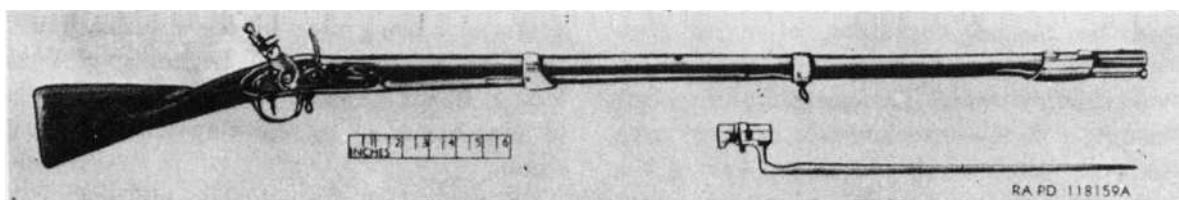
Fig. 9-1 Flintlock musket, Springfield model of 1808.

of the percussion primer early in the nineteenth century, which made use of the newly developed percussion powder that would explode when crushed, and the development of the metal cartridge case which provided effective obturation, resulted in the adoption of the breech loading system. Then the use of rifling became practicable in all weapons. The first successful breech loader appeared in 1838, while the self-contained cartridge (bullet, propellant, and primer in one unit) came into use eight years later. It was in 1842 that the Army finally adopted the percussion system, modifying its large stocks of flintlocks to produce the percussion lock rifles that served through the Civil War period.

As weapons improved and better ammunition became available, the magazine rifle was developed to meet the demand for increased firepower. The famous Winchester '73 was among the early successful magazine rifles. It provided a magazine which held several rounds of ammunition, and means for transferring them to the chamber. Reduction of caliber, improvement in propellants which permitted use of smaller charges, and reduction of size and weight of cartridges simplified the problem.

After the period of the Civil War interchangeability of parts was provided. This era had been ushered in by Eli Whitney (of cotton gin fame) who first applied the principle of interchangeable parts and mass production in the manufacture of a large number of rifles for the government.

The modern military rifle was perfected in all its essentials by about 1890. Since that time details have been refined, smokeless powder has replaced black powder, improved ammunition has been provided, and better metals have become available. The trend has been toward higher velocities, greater firepower, and less weight.

As early as 1902, the Chief of Ordnance recognized "the possible desirability of the substitution of a semiautomatic musket for the hand operated magazine rifle." The mechanical invention necessary to fill this need, however, required more than thirty years of development. Among the major problems was that of making the action sufficiently rugged and dependable, for the Army wanted to use the standard cal. .30 cartridge, as well as to fill strict military specifications. The U.S. rifle cal. .30, M1, was adopted as standard in 1936.

9-1.2 DEVELOPMENT OF AUTOMATIC WEAPONS

The development of automatic features and of full automatic weapons was in response to the demand for increased firepower. The early weapons employed multiple barrels on a single mount, which could be fired simultaneously. Other arrangements which were developed permitted the firing of multiple barrels successively, or brought multiple chambers successively to a single barrel. These did increase considerably the volume or rapidity of fire but automatic loading had not yet been worked out. Moreover, they were very heavy and cumbersome.

The development of automatic weapons was hastened by the invention of the percussion primer, the adoption of breech loading, and introduction of complete rounds assembled in a metal cartridge case. The first practicable machine gun was the Gatling, invented by Dr. Gatling about the time of the Civil War (Figure 9-2). Its adoption was followed by others of the same general type, which in effect combined in one mount a considerable number of breech loading rifles that could be loaded and fired mechanically.

In 1884 Sir Hiram Maxim, an American engineer, designed the first truly automatic machine gun. It employed a single barrel and utilized the principle of recoil operation to secure continuous and automatic functioning as long as the trigger was held down. This weapon was an immediate success; the soundness of its design and principle of operation were immediately recognized. It revolutionized machine gun tactics and stimulated the development of other automatic types. In modified and improved form it was still being used by the British, German, and Russian armies at the beginning of World War I; it has appeared also among the variety of weapons used by the communist forces in Korea.

The principle of gas operation, utilizing a small portion of the expanding powder gas, was first successfully employed by John M. Browning,
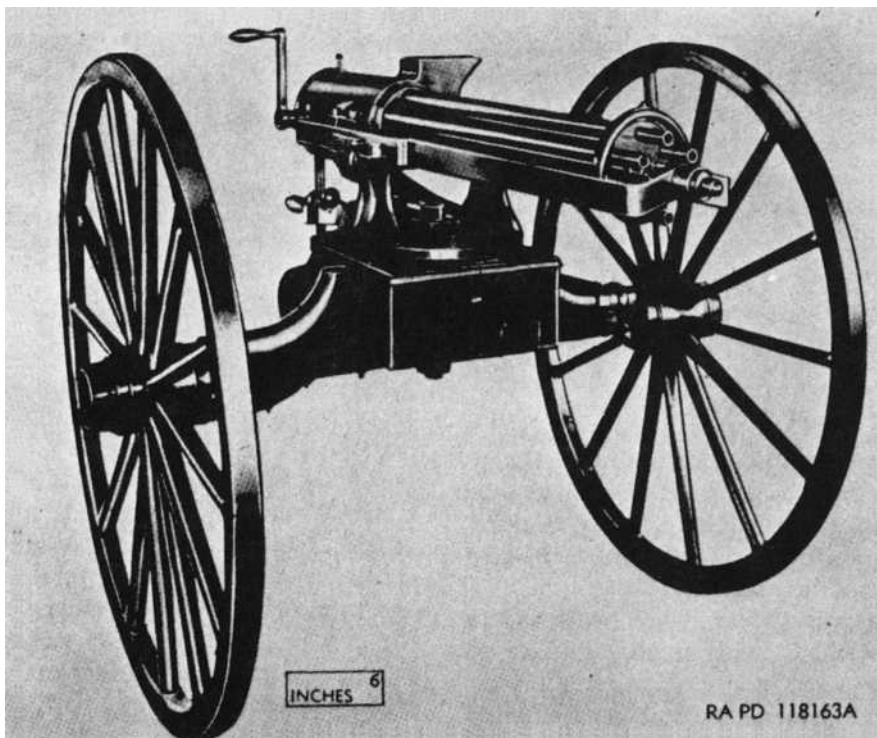
Fig. 9-2 Gatling gun.

an American, who brought out the Colt machine gun in 1889. This was followed by the Hotchkiss, employing the same system of operation. During the period covering World War I, Browning's short recoil machine gun, which was originally patented in 1901, reached the stage of development very much as it is today. The Browning Automatic Rifle, (BAR), answering the need to combine the light weight and flexibility of the conventional rifle with the greater firepower of the machine gun, has served also through the two World Wars.

9-2 CLASSIFICATION OF MILITARY SMALL ARMS

A definition of small arms must be approached with care, for the dividing line between small arms and artillery is not a stable one. In general, as compared to artillery, small arms are actually small arms, hand transportable in combat. We may undertake a definition for the purposes of today's weapons in the following form: small arms are those firearms whose caliber is not greater than 20 mm (cal. .79). A recent exception to this definition is a proposed 30-mm automatic aircraft gun; this gun and the 20-mm aircraft gun would formerly have been called cannon, but in their employment they fit the role of what we wish to call arms. In some discussions the shoulder fired rocket launcher and recoilless rifle are also called small arms.

There are three main types of small arms: (1) hand weapons, (2) shoulder weapons, and (3) machine guns. These distinctions are not rigid and, depending upon the weapon, sometimes overlap.
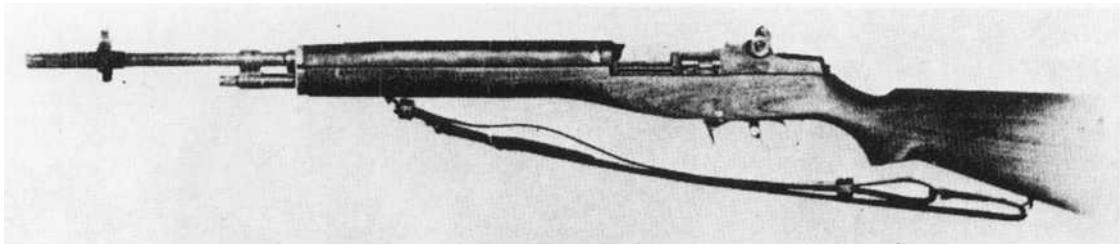
Fig. 9-3 Rifle 7.62-mm (NATO) M14.

9-2.1 HAND WEAPONS

Hand weapons are those fired with one hand. A revolver is a hand weapon that fires successive shots by means of a revolving cylinder. A pistol is a hand weapon that provides for the feeding of cartridges from a magazine.

The revolver is the older of the two forms of hand weapons and is being rapidly superseded by the pistol in most of the world's military organizations. The principal advantages of the pistol over the revolver are: it allows faster loading, it is simpler and compact in construction, and it is easier to clean and maintain.

9-2.2 SHOULDER WEAPONS

Shoulder weapons are those weapons normally fired from the shoulder and supported by the shoulder and the hands. They include rifles, (see Figure 9-3), carbines, shotguns, and submachine guns.

(a) Rifles are shoulder weapons, capable of considerably greater range and accuracy than hand weapons. Military rifles are usually sighted up to approximately 1200 yards in range. Practical consideration, such as the fact that the front sight will obliterate from view a man-sized target at ranges greater than 600 yards, confines the effective range to approximately that distance. The greater stability provided by the use of both hands and the shoulder, combined with the superior sighting qualities of the rifle, permits considerably greater accuracy than a hand weapon, even at normal pistol range. The barrel length of most military rifles is approximately 24 inches; barrel length formerly varied between 24 and 31 inches. It was eventually shortened for convenience in carrying and handling at a slight sacrifice in velocity and sighting accuracy. Military rifles may be classified as manually operated or as semiautomatic (self-loading). Their operation will be considered later.

(b) Carbines are essentially short barreled rifles. While they do not have as great a range as rifles, because of their short barrels, their shorter length and lighter weight facilitate their use from vehicles and in other situations where the greater length of a rifle would be disadvantageous. Carbines are either manually operated or semiautomatic.

(c) Shotguns are shoulder weapons with smooth or unrifled bores, designed for the discharge of a mass of round pellets called shot. The Army uses various types of shotguns, all of which are commercially manufactured with very slight, or no changes incorporated to adapt them to military use.

(d) Submachine guns are shoulder weapons designed for close range dispersion fire. Their short length facilitates their use from vehicles, and they are capable of delivering a heavy volume of fire in a minimum of time. The submachine gun is essentially a weapon of opportunity, and is used to protect the personnel of crew served weapons, small groups of personnel, or wherever a heavy volume of fire is needed in a close combat situation.

9-2.3 MACHINE GUNS

A machine gun (see Figure 9-4) is a fully automatic weapon, capable of sustained fire. These weapons are fired from a mount, which may be either a fixed or flexible type, and may be capable of adjustment to give controlled direction to the gun. Machine guns are fed by a detachable magazine, charger strip, hopper, or belt. In order to meet the American Army's requirements for a machine gun, the weapon must be belt fed. Weapons which normally employ
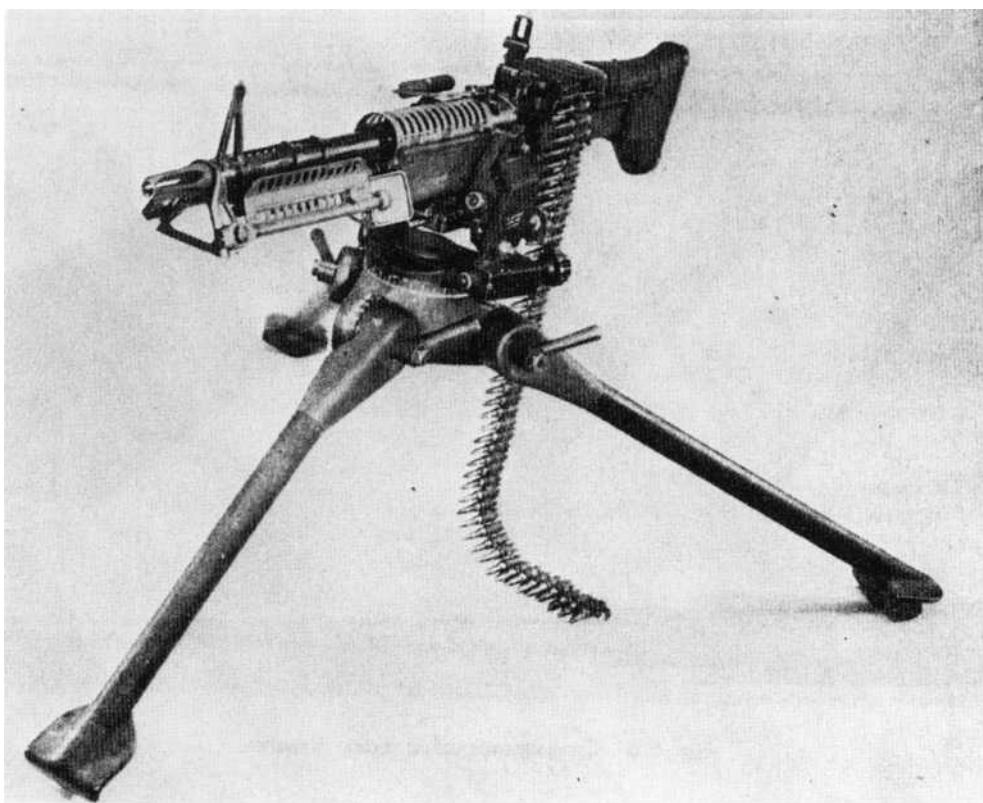
Fig. 9-4 Machine gun 7.62-mm (NATO) M60.

automatic fire will become hot rapidly, and require a means of cooling. Thus, we have air cooled and liquid cooled machine guns. Machine guns are classified, according to their weight, as light or heavy. A weapon which weighs less than 35 pounds is a light machine gun. If the weight is 35 pounds or more it is classified as heavy.

9-3 BASIC COMPONENTS OF A FIREARM

The components needed to fire ammunition safely, accurately, and with the highest required velocity may be considered to constitute the basic firearm. Every small arms weapon, regardless of type, must have four basic components: (1) receiver; (2) barrel; (3) breech mechanism (bolt); and (4) firing mechanism (Figure 9-5).

9-3.1 RECEIVER

The receiver is the metal housing about which the whole weapon is assembled. Its counterpart on the artillery piece is the breech ring. The purposes of the receiver are:

(a) To hold the breech end of the barrel.

(b) To house the bolt (or breechblock).

(c) To house the firing mechanism (trigger, hammer, sear).

(d) To hold the ejector (usually).

(e) To hold the stock (grips in some weapons).

(f) To hold the feed mechanism.
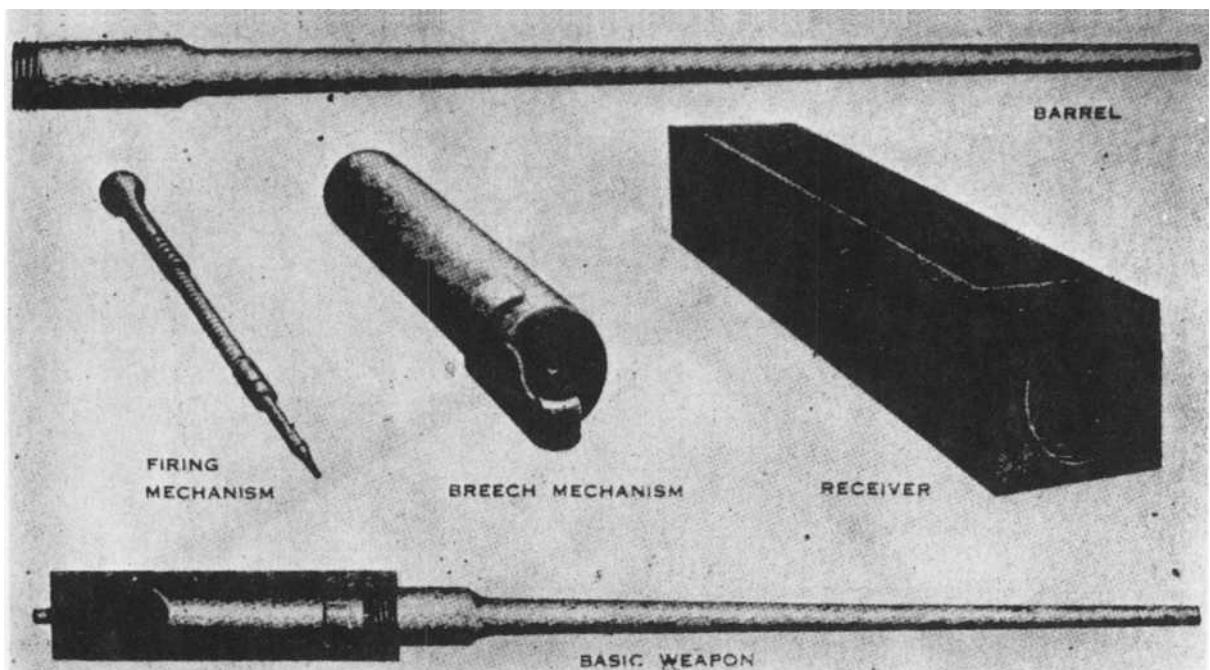
Fig. 9-5 Components of a basic firearm.

9-3.2 BARREL

The barrel is similar to the artillery tube and has, in general, the same components (chamber, bore, etc.). The bore of the barrel is rifled to give the bullet rotation for stability in flight. The maximum diameter of the bullet is slightly greater than the diameter of the bore between lands, so that as the bullet travels down the bore the lands engrave the gilding metal jacket of the bullet, thus imparting rotation and providing a seal which prevents the forward escape of the gas.

Of the several types of rifling twist found among small arms, only one type, uniform twist, is used presently in the rifling of U.S. military small arms weapons; and the direction of twist is almost universally right hand, so that the rotation of the bullet is clockwise as viewed from the breech end. One notable exception is the cal. .45 pistol, M1911A1, which has 6 lands and grooves and uniform left hand twist. The rifling of the cal. .30 rifle, M1, has four lands and four grooves, right hand twist, and one turn in 10 inches; the rifling is identified by the abbreviations: 4R 10.

9-3.3 BREECH MECHANISM

To be effective a breech mechanism must be safe, provide a secure lock to prevent opening under the terrific gas pressure during firing, and minimize the danger of premature discharge. It must operate smoothly and rapidly and its parts must be strong and durable. The parts should be designed to permit easy disassembly for proper cleaning after firing, and for quick repair so that the mechanism will not be disabled for long periods of time. Most of the individual parts should be interchangeable in mechanisms of the same model. Mechanically, the bolt incorporates the locking device, firing mechanism, and extracting device.

The locking of the breech mechanism may be accomplished in any of several ways. It may consist, as in the cal. .30 rifle, M1, of two lugs protruding from the sides of the bolt. These lugs enter deep notches in the receiver when the bolt is rotated in its forward position. On some weapons a sliding or hinged block moves into a recess locking the bolt against the receiver. The Browning machine guns and the Browning Automatic Rifle (BAR) use variations of this idea.

On some other automatic weapons, such as the cal. .45 submachine gun, M3A1, the bolt has no locking device, but depends upon its inertia to keep the breech closed until the propellent gas pressure has dropped to a safe limit.

9-3.4 FIRING MECHANISM

The firing mechanism (Figure 9-6) is a firing pin or striker usually housed in the bolt or breechblock. Its purpose is to move forward, strike the primer, and fire the cartridge; this is accomplished with the help of firing components such as the hammer, sear, and trigger. Firing pins are classified as movable or fixed.

A movable firing pin is a steel rod that runs longitudinally thru the bolt and is driven forward either by spring expansion or hammer action. There are three types of movable firing pins: A free floating firing pin is driven forward by a sharp blow of a hammer and is retracted by cam action. An example of this type of mechanism is found in the cal. .30 rifle, M1. No spring force is used on either the forward or rearward movement of the pin. The percussion firing pin is driven forward by the force of a compressed driving spring. This type of mechanism is cocked by engaging a projection on the firing pin (in this case, usually referred to as a striker) with a sear, connected to the receiver. When the bolt or other type of breechblock is moved forward the firing pin spring is compressed. Bolt action rifles and numerous pocket type pistols use this type of mechanism. An inertia firing pin is shorter than the length of the recess in which it is housed. This type of pin incorporates an excellent automatic safety device into the weapon in which it is used, as it requires a full, intentional blow of the hammer in order to function as intended. A spring, compressed on the forward movement, retracts the pin to its rear position after firing. This type of firing pin is used on the caliber .45 pistol, M1911A1. A fixed firing pin is an integral part of the bolt or hammer of a weapon. In the case of the submachine gun, M3A1, it is a projection on the face of the bolt. When the bolt moves forward the firing pin strikes the primer of the cartridge as the round becomes fully chambered.

The hammer, sear, and trigger are shown in Figure 9-7. A sear is defined as a catch that holds
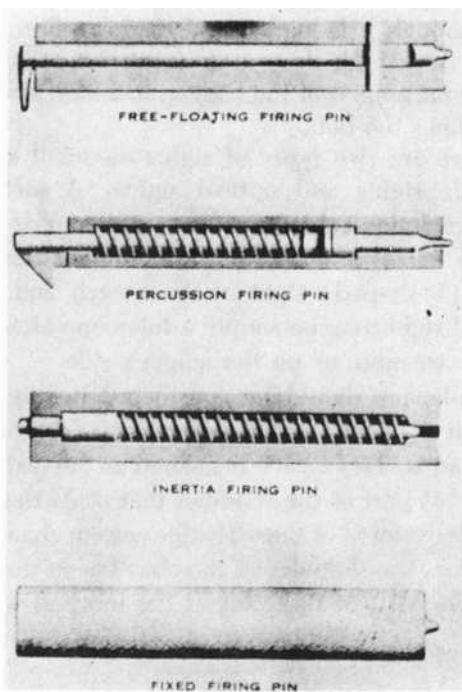

Fig. 9-6 Firing mechanisms.
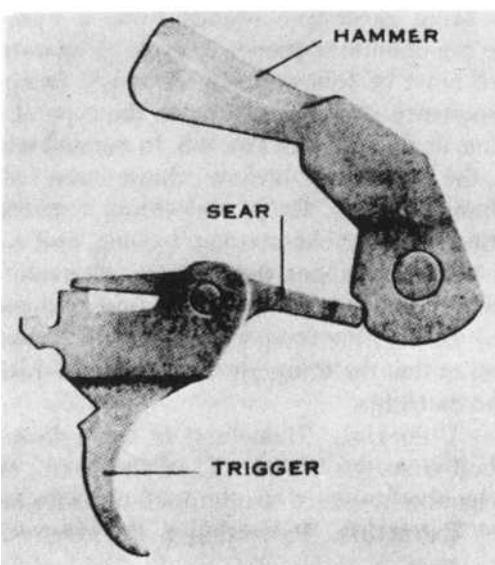
Fig. 9-7 Firing components.

the hammer or firing pin, or sometimes the bolt, in a cocked or nonfiring position until the trigger is squeezed.

Although not a part of the firearm in the sense that they are needed for firing, the safety mechanism and the sighting devices are essential components. The weapon must be safe to handle

even though it is loaded and ready to fire. The safety device fills this requirement if it positively blocks movement of the trigger, hammer, sear, or sometimes the bolt.

There are two types of sights on small arms: metallic sights and optical sights. A metallic sight includes a blade sight at the muzzle end of the barrel and an aperture, folding leaf, or open (U-shaped) sight at the breech end. An optical sight may be simply a telescope attached to the weapon, as on the sniper's rifle.

Headspace should be considered in any discussion of safety and dependability features in small arms. Headspace is defined as the distance from that part of the chamber that stops the forward movement of the cartridge case in chambering (e.g., the shoulder of the chamber in the cal. .30 rifle, M1) to that part of the weapon which

stops the rearward movement of the cartridge case when firing takes place, i.e., the face of the bolt. If this dimension is too large there will be excessive headspace, and the pressure of firing will usually rupture the case and allow gases to escape, endangering the firer as well as lowering the chamber pressure. If the headspace is too small the bolt may not close or the cartridge case may be damaged in the chambering step; the latter result would lessen the initial volume for the combustion of the propellant, i.e., increase the density of loading, and cause excessive, possibly dangerous pressure to be built up. Faulty headspace, causing damage to cartridge cases, may also cause difficulty in the extraction of the case after firing. In most weapons, an adjustment of the headspace must be made whenever a barrel or bolt is changed; the importance of this adjustment should be appreciated.

9-4 CYCLE OF OPERATION

In firing successive rounds from a weapon, there is a definite sequence or cycle of operations which must be followed. In automatic weapons the sequence varies according to the type of operation, as discussed in Par. 9-5. In manual weapons the cycle is broken down into eight mechanical steps: firing, unlocking, extracting, ejecting, feeding, chambering, locking, and cocking. For all weapons the cycle is relatively the same, although not always in the same sequence.

(a) Firing. Firing is the tripping of a sear or spring so that the firing pin may strike the primer of the cartridge.

(b) Unlocking. Unlocking is the release of the bolt from the breech end of the barrel after the chamber pressure has dropped to a safe limit.

(c) Extracting. Extracting is the removal of

the cartridge case from the chamber after firing.

(d) Ejecting. Ejecting is the expulsion of the cartridge case from the weapon after it has been withdrawn from the chamber.

(e) Feeding. Feeding is the transfer of a new round into a position between the chamber and the bolt.

(f) Chambering. Chambering is moving the new round forward into the chamber as the bolt closes.

(g) Locking. Locking is the sealing of the breech end of the barrel to contain the high chamber pressure.

(h) Cocking. Cocking is the retraction of the firing mechanism to provide sufficient energy for the firing pin to strike and fire the cartridge.

9-5 BASIC TYPES OF OPERATION

The type of operation which supplies the force for firearms to function may be manual, recoil, gas, or blowback. Weapons using the last three types of operation are referred to as automatic or semiautomatic. Automatic means that the

weapon is capable of firing a burst or succession of shots by a single, continuous depression of the trigger. Semiautomatic means that the weapon is capable of firing only a single shot with each pull of the trigger.

9-5.1 MANUAL

A manually operated weapon requires human energy to perform the phases of operation, including loading, firing, and ejecting the cartridge. Thus its fire cannot be automatic or semiautomatic. The action is designed to be simple and fast, however, requiring only a minimum of operating effort. Manually operated weapons are fast disappearing from the military scene. The bolt action rifle is a classic example of a manually operated rifle.

9-5.2 RECOIL

Recoil operation utilizes the rearward thrust of the cartridge case against the face of the bolt (the kick of the weapon) to push the bolt, barrel, and other parts rearward. This rearward movement of the barrel and bolt inside the receiver causes cams to unlock the breech and actuate the operating mechanisms. Springs are used to return the recoiling parts to battery. In recoil operation the bolt is locked positively (mechanically) during firing. It must remain locked and must recoil simultaneously with the other parts until the gas pressure has subsided, so that it will not endanger the operator by releasing high pressure gas into the action. After the bullet has left the barrel, unlocking takes place; the moving parts separate; and the bolt travels to the rear.

9-5.3 GAS

Gas operated weapons utilize a portion of the expanding propellent gases to unlock the breech mechanism and move it to the rear. This is usually accomplished by using the gas, diverted from the barrel through the gas port, to move a piston, which in turn is connected to the bolt or breech mechanism. The resulting motion unlocks the bolt from the receiver; drives the bolt to the rear; and transmits the energy for all required operations. As in recoil operated weapons, a spring is used to store energy for the forward motion. The barrel does not move with respect to the receiver. Gas operation is adaptable to either automatic or semiautomatic actions.

9-5.4 BLOWBACK

Blowback operation utilizes the pressure of the propellent gases in the barrel to force the bolt to the rear. It provides no device or mechanism for locking the breech. The inertia of a very heavy bolt or slide, backed by a powerful spring, keeps the cartridge case seated in the chamber during the short period of time necessary for safety. In weapons firing from an open bolt position, the round is fired before the bolt is fully forward so that the blowback force must overcome the final momentum of the bolt and impart a rearward momentum before the breech is opened.

Blowback is the simplest form of operation on automatic or semiautomatic weapons and is ideally suited to submachine guns and relatively low pressure semiautomatic pistols. The cal. .45 pistol, M1911, is recoil operated, but not blowback. The M3 submachine gun has a blowback type of operation. This system is not used in weapons that fire high pressure ammunition, because an unreasonably heavy bolt would be required.

The principal difference between recoil and blowback operation hinges on the presence or absence of a method of locking the breech. If no form of lock or mechanical disadvantage, other than the weight of the recoiling parts and the tension of certain springs, is present, the weapon is said to be blowback operated. If any form of lock or mechanical disadvantage is incorporated into the action, such as locking cam surfaces, rotation of the barrel, or pivoted linkage, the weapon is said to be recoil operated.

9-6 CURRENT PROBLEMS AND TRENDS OF DEVELOPMENT

The small arms designer of today is faced with problems which are so complex and varied that development in the field has become slow. However, progress is not stagnant, and since the termination of World War II, every small arms weapon has been evaluated with a view towards
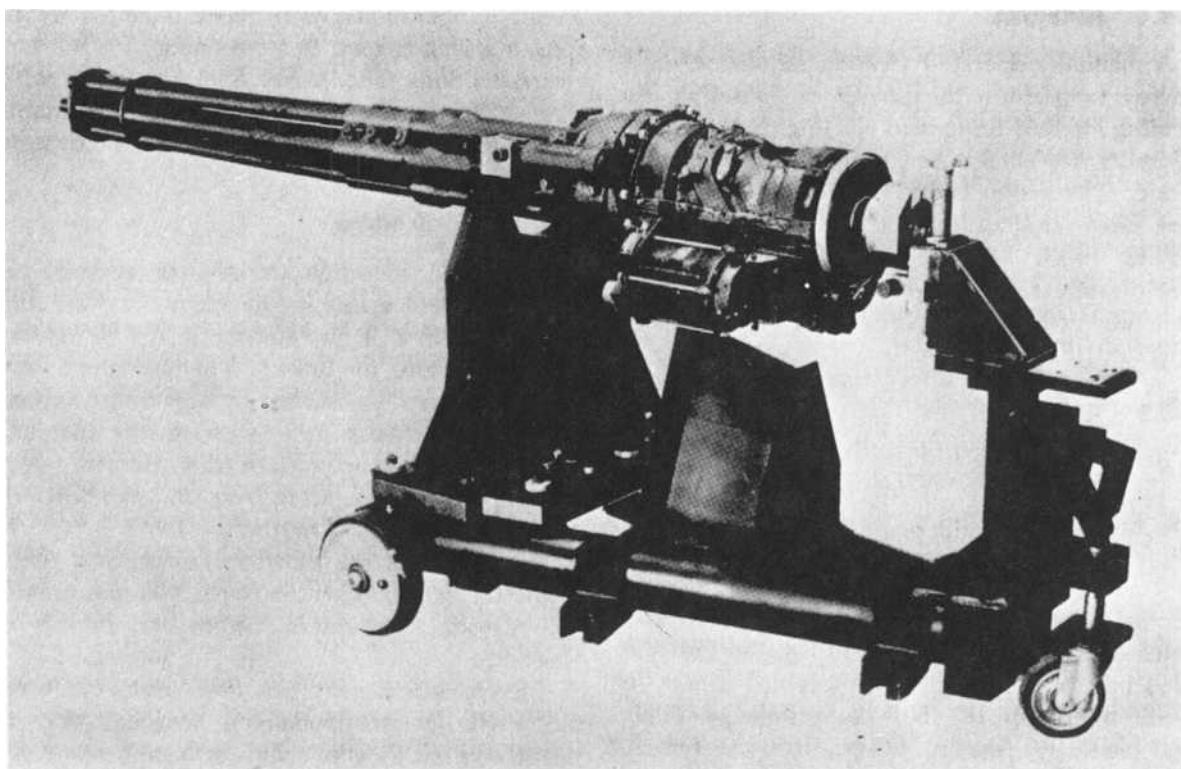
Fig. 9-8   Gun 20-mm T171E3 (six rotating barrels) on test mount.

reducing the total number of weapons employed and at the same time improving the overall characteristics. The present quest is for less weight and greater firepower (Figure 9-8). As ideas for accomplishing these become development trends, associated problems involving recoil, strength, heat, erosion, corrosion, lubrication, and production are involved to an extent not encountered before.

9-6.1   RECOIL

The requirement of developing a rifle of minimum weight, capable of projecting a bullet of given size and weight at a specified velocity. This presents to the designer a problem basic to all small arms design: the efficient absorption and dissipation of energy. If a certain mass is to be propelled from a rifle barrel at extreme acceleration, the reaction to the force causing the acceleration must be capable of being withstood by the firer. In the light of current knowledge, there are four ways of absorbing enough of this reaction force to permit a man to hold and fire the weapon:

(a) Have the mass of the weapon great enough to absorb some of the energy.

(b) Have some sort of built in recoil system.

(c) Incorporate a muzzle brake or compensator.

(d) Provide a gas tap off to the rear on the recoilless principle.

Each of these four energy absorption methods has been used at one time or another in the history of small arms development; however, for the sake of simplicity and safety, the first named has been most widely used. Experiment is presently under way on the use of compensators, which act in the manner of a muzzle brake to reduce recoil, since the reduction in weight of the piece means less mass to absorb recoil energy.

9-6.2 STRENGTH

Reduced weight also poses the problem of maintaining sufficient strength to withstand the force of firing grenades (roughly one additional pound of weight is required on the M14 to enable the rifle to withstand grenade launching) and the rugged treatment unavoidable in training and combat. Experiment in this direction is concerned with plastic stocks and stamped (hollow) metallic (e.g., aluminum) stocks and handguards with a plastic, rubberlike coating for desirable handling characteristics. The development of lighter stronger metal plays a large part in weapons engineering, and it is apparent that the small arms designer must not only have a complete knowledge of basic weapon action but must also be something of a metallurgist in his own right.

9-6.3 HEAT AND EROSION

The problem of erosion is a problem both in temperature control and in metallurgy. This problem is, of course, accentuated in automatic weapons. A high rate of fire generates a great amount of heat. The temperature of the barrel rises, the steel weakens, erosion occurs more rapidly, muzzle velocity drops, and accuracy is lost. Erosion is, of course, most severe near the breech, but is also a problem in the remainder of the bore.

The barrel temperatures of ground weapons are held to a minimum basically in two ways: by heat transfer using a liquid coolant within a jacket around the barrel; and by direct heat conduction through the barrel steel to the surrounding air convection currents.

Of the two methods of cooling, water cooling is the most effective. However, this system increases the weight of the weapon and reduces mobility. The barrel is encased in a jacket which holds water to cool the barrel during firing.

Although not as effective as water cooling, air cooling is simple and reduces the weight requirement. Air contact with the barrel dissipates the heat. Aircraft weapons, which may be openly exposed to a great rush of air when the plane is in flight, can have relatively light barrels. This simple exposure, however, is not sufficient in ground weapons, and integral fins, ribs, or rings may be added to the barrel.

The trend today is toward the use of heavy, air cooled barrels of special alloy steels that retain normal properties throughout a wide temperature range. This provides increased mass and greater heat capacity and will keep temperatures within reasonable limits. Thus to increase heat capacity these barrels are several times larger than would be necessary for ballistic strength requirements.

A further step in the control of erosion is the standard practice at Springfield Armory of inserting a 9-inch stellite liner in the breech end of aircraft machine guns and plating the remainder of the bore with chromium. Stellite is a nonferrous alloy consisting primarily of cobalt and chromium. It is a very hard material, and of greatest importance, it retains its hardness at high operating temperatures. The chrome plating in the bore also retards erosion.

9-6.4 CORROSION

The role of the metallurgist is an important one also in connection with the corrosion of metal. There are three finishes in general use by the Ordnance Corps for finishing small arms and parts thereof:

(a) Parkerizing, a zinc base phosphate.

(b) Parco Lubrite, a manganese base phosphate.

(c) Pentrate, an oxide.

Parkerizing is by far the most efficient and durable rust preventive finish and is therefore in very wide use by the Ordnance Corps in large manufacturing and depot installations.

On some small moving parts which have close tolerances Parkerizing and Parco Lubrite cannot be used, because the slight amount of build up which occurs in phosphating will change the dimensions of the parts. The texture of a phosphated surface increases friction and is therefore not used on such parts as cams; however, such a surface is more resistant to abrasion than a Pentrate finish.

Although Pentrate is at the bottom of the list as a rust resistant finish, it is in wide use because of its simplicity of application and the fact that it causes no change in the size of parts, there being actually a surface penetration of .00035 to .00045 inches. The blue finish sometimes seen of commercially produced small arms is an oxidized finish similar to a Pentrate finish.

Two types of finishes are used on the same weapon in many cases in small arms. For example, the Browning Machine Gun, cal. .30, M1919A6, has a Parkerized receiver, barrel jacket, and barrel, but the bolt and other small moving parts are finished with Pentrate.

9-6.5 LUBRICATION

Whether or not a weapon requires frequent lubrication is an important consideration in gun design. Several fine actions have been developed only to be rejected because of the operational requirement of careful and continuous lubrication of moving parts. It is important also that it be unnecessary to lubricate the cartridges to insure proper functioning, because of the dirt and grit to which ammunition is subjected in the field.

Considerable attention is being given to the operation and maintenance of weapons under arctic conditions and other severe climatic conditions. In addition to the weapons design problem, this presents, of course, problems in explosives and in lubricants.

9-6.6 PRODUCTION

Suitability of the weapon for mass production at minimum cost is another must for the military small arms designer. At the same time, however, care must be taken that in reducing production problems critical dimensions are not changed to the extent that functioning is impaired.

The importance of designing with mass production in mind will be appreciated when it is recalled that small arms are used in vast numbers. During the years 1940-1945, Springfield Armory alone produced over 4,000,000 M1 rifles, with a peak production of 122,000 rifles per month. During this period increasingly efficient mass production methods brought the direct labor and material cost per rifle down from the original $214.54 to $26.06.

9-7 RECOILLESS RIFLES—INTRODUCTION

The rapid movement of modern warfare has given emphasis to the long recognized necessity of providing the infantryman with increased firepower. One of the first steps toward hand artillery for the infantry was the rifle grenade. This makes the rifle a large caliber weapon, but, of course, range is short, accuracy is poor, and the recoil is considerable. The shoulder fired bazooka rocket launcher which appeared in 1943, solved the recoil problem, and being actually recoilless, improved the range and accuracy, and fired a larger projectile, but there was an urgency for still greater accuracy and range. This led to an investigation of the practicability of firing a conventional type projectile from a weapon which would counteract recoil by the discharge of a portion of the gases from the propellant, i.e., leaving the rocket motor behind in the gun, so to speak, and still letting the exhaust gases escape from the rear. Such a recoilless artillery piece would eliminate the need for a recoil mechanism and materially decrease the weight of the mount, giving the soldier hand artillery. The recoilless rifle, in 57-mm and 75-mm versions, made its debut in 1945, and a 105-mm rifle followed soon after.

9-8 GENERAL CHARACTERISTICS

A recoilless rifle delivers no recoil to its mount or, if it is shoulder fired, to the person of the firer. The recoilless rifles of the American army are large caliber weapons of light weight, great striking power, and accuracy. They can be carried by hand and, in the case of the 57-mm rifle (Figure 9-9), fired from the shoulder. Whereas a howitzer may weigh one hundred times as much as the projectile it fires, a recoilless rifle weighs only about ten times the weight of its projectile. A price is paid for this, however, in that the complete round is heavier for the recoilless rifle.

Although recoilless rifles are in one sense light
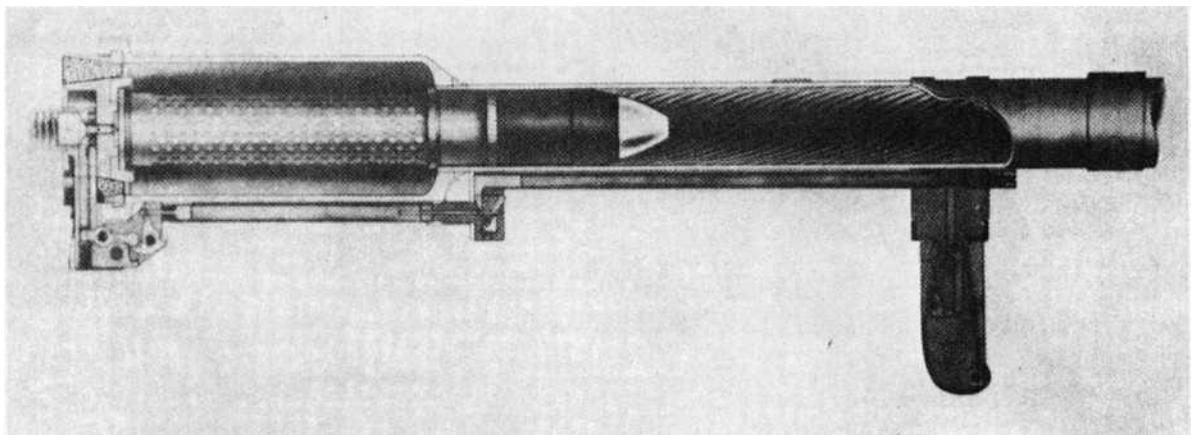
Fig. 9-9 Phantom view of recoilless rifle showing loaded round, trigger linkage, breech, and firing mechanism.

artillery pieces, in concept, design, and tactical employment they might be classified with small arms, in that they are weapons carried and used by the individual man or a small team of men.

The recoilless rifle has an abnormally large chamber (Figure 9-9) and is only partially closed at the rear by the breechblock which contains the nozzles or venturis for the rearward release of the gas.

Like the standard artillery piece the recoilless weapon has a rifled bore and fires a conventional projectile with a standard fuze, although the rotating band on the projectile is pre-engraved. The ammunition in use is a fixed type in which the cartridge case differs from the conventional in that it permits escape of the gases to the rear through perforations in its walls after a certain comparatively low pressure has been reached. The density of loading is high in these rounds.

The recoilless round of ammunition differs from the rocket (as does the standard artillery complete round) in that the projectile or payload is the only part that travels from the weapon after the propelling charge is expended.

As in any mobile weapon design, weight and size are critical factors. Increase in maximum pressure would require increased strength and greater weight. Increased projectile travel would permit a decrease in pressure but an increase in weapon length and weight. An increase of the ratio of average pressure to maximum pressure could be attained, as in conventional guns, by an adjustment of loading density, powder web, and weight of propellent charge. Such a change would reduce the maximum pressure and the travel at the expense of increased complete round weight. No practical solution near the ideal exists. The opposed weight and ballistic performance criteria are compromised to yield the basic proportions incorporated in American recoilless rifles.

9-9   PRINCIPLE OF OPERATION

In a closed mechanical system, acted upon by internal forces only, the total change in momentum imparted to all the elements of the system in a given period of time must equal zero. This is described by Newton's laws of motion. In conventional guns (Figure 9-10), recoil mechanisms notwithstanding, great external force must be applied through the carriage to keep the carriage in equilibrium. Similarly, the kick and recoil one experiences when firing a rifle is evidence
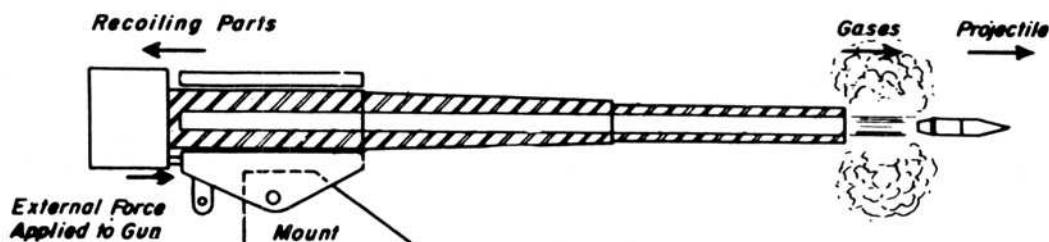
Fig. 9-10   Standard artillery piece.
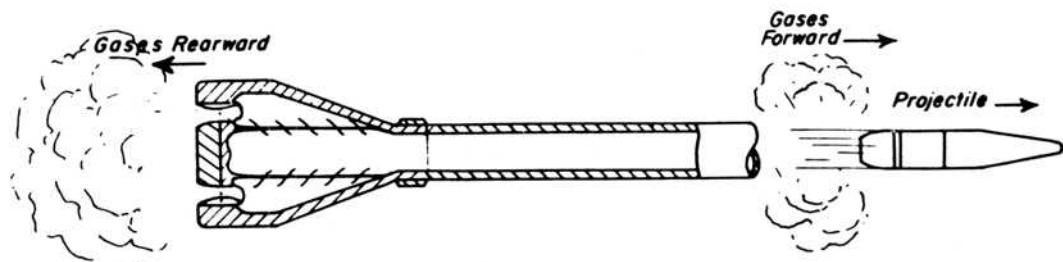
Fig. 9-11   Recoilless rifle.

of the external force he must exert to hold the weapon. Neither of these types of weapons, therefore, is a closed mechanical system. But if we ask for a weapon which fires a projectile and yet sustains no force from its mount, a recoilless weapon, then this weapon we seek is subject to the laws of a closed mechanical system, and the net momentum obtained in the system as a result of firing must equal zero.

The elements of this system are indicated schematically in Figure 9-11. The projectile is one element, moving forward. Let its mass be m_1 and its velocity be v_1. Some of the propellent gases, of mass m_2, move forward, too, behind the projectile with some velocity v_2; but most of the gases, a mass m_3, escape to the rear through the nozzles, with a discharge velocity v_3. The recoilless rifle itself should have zero momentum, i.e., be stationary, as a result of the firing. Let its mass be m_4 and its velocity be v_4. All velocities are taken at the same time. Now, the law given above may be stated in the following equation, taking each velocity to be positive in the direction of the corresponding arrow (Figure 9-11):

$$m_1v_1 \quad + \quad m_2v_2 \quad - \quad m_3v_3 \quad \pm \quad m_4v_4$$

(Projectile (Forward (Rearward (Recoilless
Gases)   Gases)   Gases)   Rifle)

$$= 0. \qquad (9\text{-}1)$$

Thus, for the rifle to be recoilless ($v_4 = 0$), we must have

$$m_3v_3 = m_1v_1 + m_2v_2. \qquad (9\text{-}2)$$

That is, the momenta of the forward moving projectile and gases must be equal and opposite in direction to the momentum of the rearward moving gases discharged through the breech.

The forces of propulsion are operative for only about 0.01 second. If (9-2) holds true for velocities of the gases and projectile at all times during this firing period, then the momentum of the weapon, m_4v_4, must equal zero at all times during firing, and the net force on the weapon at each instant must equal zero. This situation characterizes absolute recoillessness; the force tending to make the gun recoil at each instant is opposed by an equal and opposite force. If, on the other hand, we require only that (9-2) hold true at the end of the firing period, i.e., that the final velocity and momentum of the gun equal zero, then the momentum m_4v_4 need not equal zero at all times during firing, and our weapon is said to have mean recoillessness, or be recoilless in the mean. The total momentum applied to it over the firing period is still zero, but it may sustain large forces, unneutralized during parts of

Fig. 9-12 The 75-mm rifle M20 on tripod mount.

the pressure interval and other oppositely directed forces during other portions of the interval. Recoilless rifles are usually recoilless in the mean.

Visual observation of a recoilless rifle will probably give no clue to the type of recoillessness it exhibits since, with the short time involved, no motion will be apparent with either type of balance. Mountings, however, must take account of the difference since a weapon, recoilless in mean only, may transmit tremendous stresses to a mount not sufficiently flexible to permit their absorption by the inertia of the weapon itself. An absolutely recoilless weapon will place no firing stresses on the mount. In either case the weight of the mount may be held to a minimum (Figure 9-12). Even the torque transferred to the weapon as a reaction to the rotary acceleration of the projectile is neutralized by inclination of the venturi openings with respect to the bore axis.

Let us return to (9-1) and (9-2), considering velocities to be those at the end of the firing period, to explain some more facts about recoilless rifles. Since the mass of the rearward moving gases, m_3, is small compared to the projectile mass, m_1, we can see the need for a nozzle, or nozzles, to give the jet a very high velocity and make the product $m_3 v_3$ sufficiently large. The ratio of the throat area of the nozzle to the area of the bore is roughly 1 to 1.45. If the nozzles should become restricted so that the mass m_3 is less than it should be, then (9-2) will not be satisfied, and (9-1) tells us that $m_4 v_4$, the momentum of the rifle, will have some negative value, which is to say, the piece will kick to the rear when fired. And if the nozzles should wear and become too large, then m_3 will be too great, (9-2) will not be satisfied, and (9-1) indicates that the rifle will jump forward upon firing.

9-10 MAINTAINING RECOILLESSNESS

A recoilless rifle as issued may recoil slightly because the nozzles are made somewhat under size to allow for erosion. As the nozzles erode, however, and become larger, the piece will become actually recoilless. At a still later stage of wear, the nozzles will be oversize, and the piece will jump forward slightly when fired.

To maintain the balance in recoilless rifles as the nozzles wear, three devices are currently employed on various rifles. These are discussed briefly below. It may be expected that metallurgical advances, making nozzles less subject to erosion, will render such devices unnecessary sometime in the future.

One device for keeping a recoilless rifle in balance is called a cone (Figure 9-13). Assembled to the rifle forward of the position of the breechblock when closed, the cone controls the flow of gases through the nozzles to the rear. Replacement cones of different sizes are issued with each rifle and can be installed by using unit personnel as needed.

A second device consists of a throat ring and throat blocks (Figure 9-14). As is the case with the cone, the throat ring and blocks restrict the flow of gas through the nozzles without affecting appreciably the efficiency of the nozzle contour. Like the cone, also, throat rings and blocks in several sizes are issued with the rifle and can be installed by the using unit as needed.

Still another device is a replaceable vent bushing (Figure 9-15). This contains the major part of the nozzles, the remaining part being contained in the breechblock. The replacement of the vent bushing to restore balance to a rifle, however, is a job for ordnance personnel.
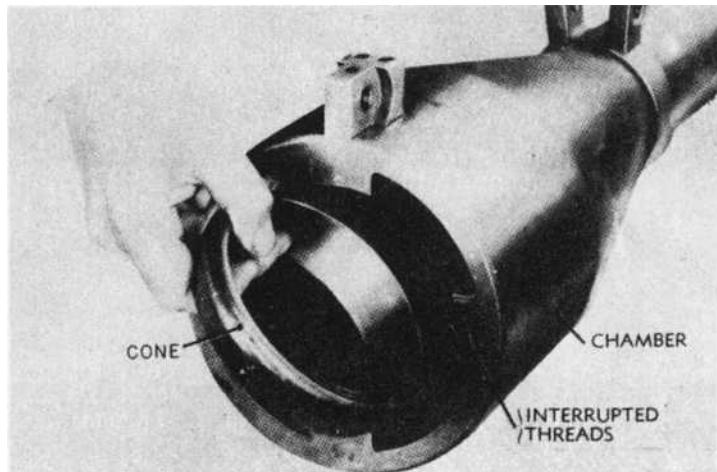

*Fig. 9-13 Replaceable cone.*
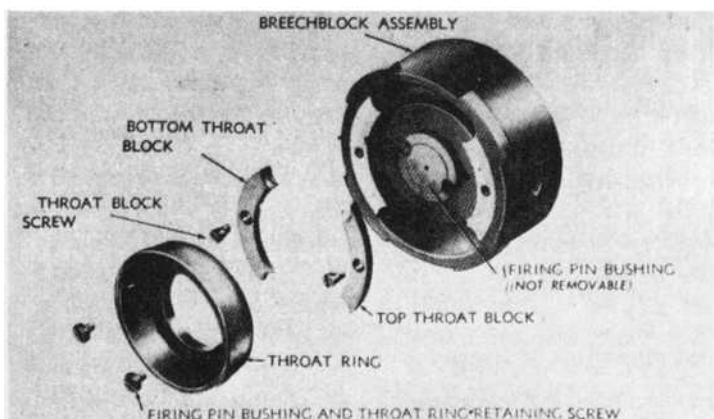
Fig. 9-14 Throat ring and throat blocks.
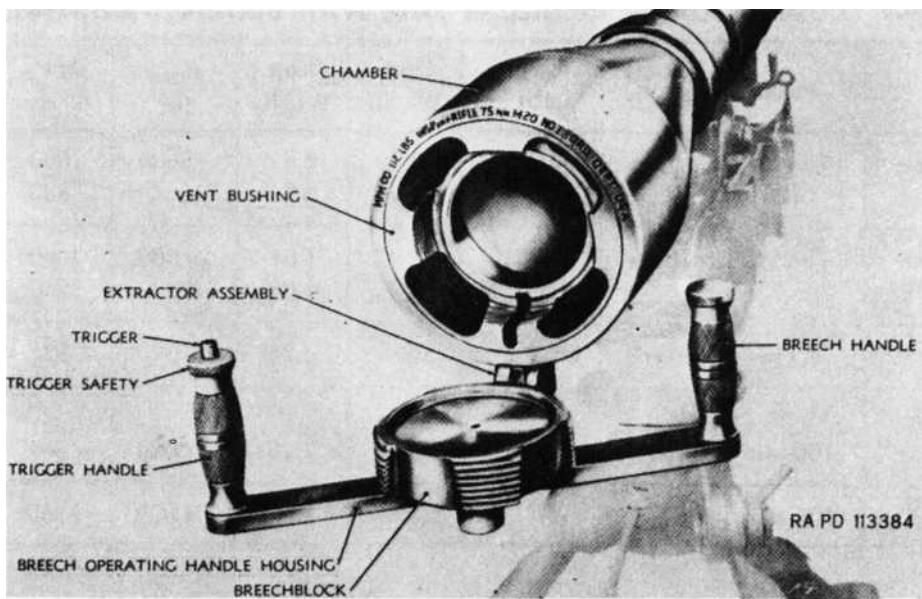
Fig. 9-15 Vent bushing.

9-11 COMPARISON OF RECOILLESS RIFLES WITH STANDARD ARTILLERY PIECES AND ROCKETS

It is always difficult to make a comparison that means anything without going in great detail into many phases of the subject. It is the purpose here to give some general data which will illustrate the three types of weapons and indicate their utility.

9-11.1 SIMPLICITY AND WEIGHT

Table 9-1 shows in a general way that the recoilless rifle has a great advantage over the standard artillery piece in weight, which has been cut down in the rifle to a small fraction of that of the howitzer of corresponding caliber. This has been done with some sacrifice in velocity and range, in most cases, and by the addition of considerable propellant. The tube of the recoilless rifle is one that must stand pressures of roughly 5000 to 10,000 psi. The ratio of average to maximum pressure is higher than for the standard artillery piece, which is to say that the pressure does not drop off as rapidly in the rifle. From necessity it must be heavier than a comparable tubular rocket launcher, which primarily must withstand the heat and blast action of the gases of the rocket, but yet considerably lighter than the tube of an artillery piece. In a standard gun the recoil mechanism adds a large percentage to the total weight of the piece. In recoilless rifles there is no recoil mechanism. In addition, the supporting carriage and spades can be very light and simple. The overall result is that weight of a recoilless piece is materially cut down over the conventional type. This may be illustrated by our 75-mm recoilless rifle which uses a cal. .30 machine gun mount, modified in a few respects to take the tube. Also, as an example, the 57-mm rifle is used as a shoulder weapon.

9-11.2 ACCELERATION AND VELOCITY

The average acceleration given a projectile fired from a recoilless rifle is of about the same magnitude as that of a standard artillery piece. The velocities are a little less than those of a howitzer of comparable caliber. However, a direct comparison of the recoilless rifle with the

TABLE 9-1 COMPARISON OF RECOILLESS RIFLE WITH STANDARD ARTILLERY PIECES

Type	Piece	Total Wt, lb	Type Rd	Proj. Wt, lb	Prop. Wt, lb	P_{max}, psi	MV, ft/sec	Range, yd
Recoilless Rifle	75-mm M20	168	HE-AT HE	13.19 14.40	2.8 2.9	9000	1000 990	7300 6960
Howitzer	75-mm	1440	HE-AT HE	13.37 14.7	1.04 1.06	29,000	1000 1250	9620
Rocket	4.5 in.	—	HE	—	4.75	—	865	4000
Recoilless Rifle	106-mm	274	HE	32.4	7.95	12,000	1650	3000
Howitzer	105-mm	4300	HE	33	3	29,000	1550	12,200

corresponding howitzer which fires the same shell with the same velocity will indicate the relative efficiency of the two weapons with respect to utilizing the available propellent energy. The howitzer requires 1.04 pounds of propellant to give the 13.37 H.E.,A.T. projectile a velocity of 1000 ft/sec; whereas the recoilless rifle requires 2.8 pounds of propellant. In accordance with (9-2), the difference of propellant weight is accounted for by the necessity of maintaining recoillessness.

9-11.3 ACCURACY AND RANGE

The accuracy and range of recoilless rifles are in general about the same as for standard artillery pieces of similar caliber and muzzle velocity, i.e., howitzers. The accuracy life of recoilless rifles is set by erosion of the nozzles, with a resulting loss of recoillessness, although it is apparently adequate for most tactical applications of the weapons. For example, the estimated useful life of the 75-mm, M20 rifle is 2000 rounds. The estimated life of the vent bushing, however, is approximately 500 rounds.

9-11.4 BLAST

The main drawback to the use of recoilless rifles is the tremendous blast that results from the escape of powder gas to the rear of the gun.

Personnel and materiel must be adequately protected for many yards to the rear.

The danger zone for the 57-mm rifle is a cone extending 50 feet to the rear of the weapon and 40 feet wide at its widest point. Personnel within 100 feet of the rear of the breech must not face the weapon because of the danger of flying particles thrown up by the blast action.

This blast has another effect in that it may be the means of enemy observation of battery locations. It would be desirable to have it reduced or eliminated. On the other hand, there have been cases in Korea in which recoilless rifles have not been identified as such by opposing forces during many days of operation.

9-11.5 TACTICAL CONSIDERATIONS

Both recoilless rifles and rockets have advantages in that at times they can be tactically employed where the gun or howitzer cannot. This would be true in terrain inaccessible to guns or where recoil forces must be considered, as on small boats or on planes. The recoil force of a gun is great and limits the size that could be fired from frail crafts without damage.

For delivery of a certain payload at the higher velocities or for great ranges, conventional artillery is better than the recoilless piece.

9-12 FUTURE DEVELOPMENTS

The now standard recoilless rifles are in part the results of compromise and expediency dictated by the urgency of wartime development. Development of larger caliber and higher muzzle velocity weapons is being actively prosecuted. Weight reductions are likewise being undertaken. Minimum possible weight in a recoilless rifle is determined by the strength of materials available for use and by energy levels dictated by projectile weight and velocity. The recoilless principle itself places no design limitation on the muzzle energy of the projectile the rifle will fire.

Blast from recoilless rifles is an inherent characteristic of their design. Methods for deflection of this blast, where such deflection is required, have been studied; but the magnitude of the blast is determined by the projectile energy and is, in its very nature, incapable of considerable reduction. Reduction of smoke and flash from recoilless rifles is being studied and progress in this direction is assured.

REFERENCES

1 W. J. Kroeger, and C. W. Musser, Frankford Arsenal Report No. R-727, *The Design of Recoilless Infantry Weapons*, Philadelphia, Pa., June 1946.

2 R. R. Studler, and W. J. Kroeger, Frankford Arsenal Report No. R-1273, *Battalion Anti-Tank Recoilless Rifles System, BAT, 106mm, M40 Rifle*, Philadelphia, Pa., March 1950 to July 1953.

3 Department of the Army Technical Manual, TM9-314, *57mm Rifles T15E13 and M18*, Washington, U.S. Government Printing Office.

4 Department of the Army Technical Manual, TM9-1901, *Artillery Ammunition*, Washington, U.S. Government Printing Office.

5 Department of the Army Technical Manual, TM0-1990, *Small Arms Ammunition*, Washington, U.S. Government Printing Office.

6 Department of the Army Technical Manual, TM9-2205, *Fundamentals of Small Arms*, Washington, U.S. Government Printing Office.

7 Department of the Army Technical Manual, TM9-2210, *Small Arms Accidents Malfunctions and Their Causes*, Washington, U.S. Government Printing Office.

8 Department of the Army Technical Manual, TM9-3058, *106mm Rifle M40*, Washington, U.S. Government Printing Office.

CHAPTER 10

DYNAMIC SYSTEMS ANALYSIS

10-1 INTRODUCTION

As weapons become more complex, their design becomes increasingly difficult. Design no longer can be accomplished by trial and error techniques or by static analysis. It now is necessary to analyze systems that move or have moving parts utilizing dynamic considerations. The process is not simple, but will save much time and expense if done carefully, prior to the manufacture of the equipment itself. Fundamentally, the analysis consists of determining the differential equation of motion and solving this equation. The solution will give the response characteristics of the system and can tell the engineer what parameters must be changed in order to obtain best weapon performance.

10-2 ANALYSIS OF AUTOMATIC WEAPONS

It has not been many years since automatic and semiautomatic weapons were principally developed by single men such as Browning, Mauser, Lewis, Colt, Garand, Thompson, Johnson, etc., using a combination of mechanical skill and a knowledge of past mistakes that we have come to call know-how. Little or none of the so-called analytical approach was considered necessary. For the last decade, however, due to demands from users for severely increased muzzle velocities and cyclic rates, there has been an ever-increasing necessity to apply the basic laws of mechanics to the working parts of new weapons. Many of the new aircraft cannon, for example, are so complex and their functioning is affected by so many variables that it would be virtually impossible (as well as prohibitively expensive) to develop them by a cut-and-dry method.

In order to illustrate the analytic approach, let us consider the dynamic problem of the movement of a bolt in the blowback operated submachine gun, the standard M3. The M3 is used in this example only as a means of illustrating the technique of analyzing a dynamic system. This example is representative of a very simple system, but the same procedure would be followed for more complex dynamic systems such as airframes, spring suspensions for automobiles, guidance packages, and a multitude of similar systems. (Refer to Chapter 2, Part 3, for a qualitative analysis of control systems.) A schematic representation of the M3 submachine gun bolt is shown in Figure 10-1. Note only a single spring is shown.

The bolt is represented by the mass M. The stiffness of the spring is denoted by its effective spring constant, k, which is the number of pounds force necessary to compress the spring one foot. Between the mass and the rigid support is shown a dashpot mechanism to represent the viscous friction or damping in the system. An external force $F(t)$ is shown acting on the mass and represents the force on the bolt due to powder gas pressure in the chamber and varies with time as the chamber pressure varies. The problem, then, is to calculate the motion as time changes of the mass M due to this external force. Or, in other words, if x is the distance between any instantaneous position of the mass during its motion and the equilibrium position, find x as a function
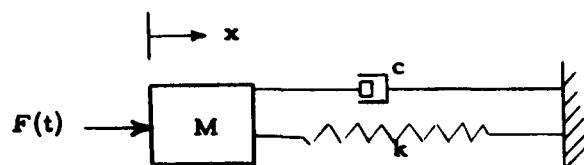

Fig. 10-1 Schematic of M3 SMG bolt.

of time. The equation of motion which is about to be derived is nothing but a mathematical expression of Newton's second law,

$$\text{Force} = \text{mass} \times \text{acceleration}$$

All forces acting on the mass will be considered positive when acting to the right (to produce a positive displacement) and negative when acting to the left.

The spring force is $-kx$ pounds. The sign of the spring force is negative because it is resisting a positive displacement.

The damping force of the dashpot is $-c\dfrac{dx}{dt}$ or $-c\dot{x}$ pounds. It is proportional to the velocity and directed opposite to it, and is, therefore, also negative.

Newton's law then gives:

$$M\frac{d^2x}{dt^2} = M\ddot{x} = F(t) - kx - c\dot{x}$$

or

$$M\ddot{x} + c\dot{x} + kx = F(t) \tag{10-1}$$

This equation is known as the differential equation of motion of a single-degree-of-freedom system. The four terms in (10-1) are the inertia force, the damping force, the spring force and the external force.

A rigorous solution of this equation becomes extremely difficult due to the manner in which the external force, $F(t)$, varies with time. This variation is shown graphically in Figure 10-2, but can be approximated analytically only by an infinite number of cosine and sine terms (a Fourier series).

Rather than tackle here a second order differential equation involving an infinite Fourier series, the solution to which requires such mathematical devices as Laplace transformations, let us examine the system in an attempt to simplify it

sufficiently to allow at least a first approximation of the solution to be obtained quickly. Figure 10-2 shows that the time during which the external force $F(t)$ acts on the mass is very small compared to the total cycle time (actually less than 1/100). This suggests that instead of treating the problem as a forced vibration, we might consider it as a free vibration with the external force determining the initial conditions. Our differential equation of motion will now reduce to:

$$M\ddot{x} + c\dot{x} + kx = 0 \text{ subject to the initial condition } v = v_0 \text{ at time } t = 0 \tag{10-2}$$

a general solution to which may be shown to be:

$$x = e^{-\frac{ct}{2M}}\left[x_0\cos qt + \left(\frac{v_0}{q} + \frac{cx_0}{2Mq}\right)\sin qt\right] \tag{10-3}$$

where

$$q = \sqrt{\frac{k}{M} - \frac{c^2}{4M^2}}, \text{ and } x_0 \text{ and } v_0 \text{ represent the}$$

initial position and velocity of the bolt at the instant of firing ($t = 0$).

Examination of an M3 submachine gun shows that the value of c is a small fraction compared to the other parameters, so, for a first approximation, c can be eliminated. This considerably simplifies (10-3) and the solution now is:

$$x = x_0\cos\omega_n t + \frac{v_0}{\omega_n}\sin\omega_n t \tag{10-4}$$

where $\omega_n = \sqrt{\dfrac{k}{M}}$ is the undamped natural frequency of the system.

In order to analyze the significance of (10-4) it will be convenient if we have only one trigonometric function in the equation rather than two. This can be accomplished by the use of algebra and a trigonometric identity.

Divide (10-4) through by the square root of the sum of the squares of the coefficients of the trigonometric terms:

$$\frac{x}{\sqrt{x_0^2 + \left(\frac{v_0}{\omega_n}\right)^2}} = \frac{x_0\cos\omega_n t}{\sqrt{x_0^2 + \left(\frac{v_0}{\omega_n}\right)^2}}$$

$$+ \frac{\frac{v_0}{\omega_n}\sin\omega_n t}{\sqrt{x_0^2 + \left(\frac{v_0}{\omega_n}\right)^2}}$$
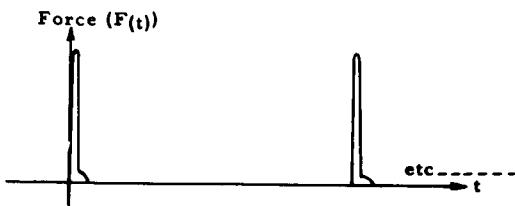

Fig. 10-2 *Forcing function of M3 SMG bolt.*

The relationship of the constant terms in the above equation can be shown in Figure 10-3.
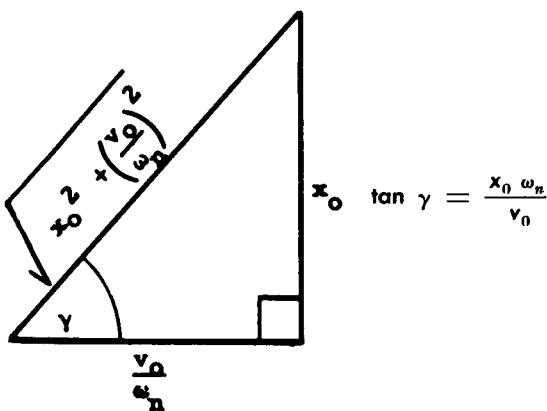
Fig. 10-3 Graphical representation of trigonometric relationships.

Thus:

$$\frac{x}{\sqrt{x_0^2 + \left(\dfrac{v_0}{\omega_n}\right)^2}} = \sin\gamma\cos\omega_n t + \cos\gamma\sin\omega_n t$$

The right side of this equation is the trigonometric identity for the sine of the sum of two angles, therefore

$$\frac{x}{\sqrt{x_0^2 + \left(\dfrac{v_0}{\omega_n}\right)^2}} = \sin(\omega_n t + \gamma)$$

or

$$x = \sqrt{x_0^2 + \left(\frac{v_0}{\omega_n}\right)^2}\ \sin(\omega_n t + \gamma) \qquad (10\text{-}5)$$

Equation (10-5) represents the position of the bolt at any time, t. The equation is a pure sine wave of maximum amplitude $\sqrt{x_0^2 + \left(\dfrac{v_0}{\omega_n}\right)^2}$, and frequency $(\omega_n t + \gamma)$. Recalling the initial conditions at $t = 0$ were x_0 and v_0, the graphical solution is easily determined, as shown in Figure 10-4.

Comparing (10-5) and Figure 10-4, it is seen that the bolt reaches its first maximum positive displacement, x_{max}, at time $T = \dfrac{\pi}{2\omega_n} - \dfrac{\gamma}{\omega_n}$. The slope of the curve at any point represents bolt velocity, so that, at x_{max}, the bolt stops and begins to close with a negative velocity. The slope at x_0 is v_0.

If the bolt is now inserted in the machine gun, and the travel of the bolt is limited to positions between x_0 and x_{max}, only the portion of Figure 10-4 which lies above x_0 will be of interest. The fully closed position of the bolt is at x_0, and the fully open position is at x_{max}. The distance between these positions is given by (10-6). The time required for the bolt to fully open is given by (10-7). The time required for the bolt to close is exactly the same.


Fig. 10-4 Plot of $x = \sqrt{x_0^2 + \left(\dfrac{v_0}{\omega_n}\right)^2}\ \sin(\omega_n t + \gamma)$.

$$x_{max} - x_0 = \sqrt{x_0{}^2 + \left(\frac{v_0}{\omega_n}\right)^2} - x_0 \qquad (10\text{-}6)$$

$$T = \frac{\frac{\pi}{2} - \gamma}{\omega_n} \text{ seconds per } \frac{1}{2} \text{ cycle} \qquad (10\text{-}7)$$

The time required for a complete cycle of operation is $2T$ seconds, so the cyclic rate of fire is:

$$CR = \frac{60}{2T} \text{ rounds per minute} \qquad (10\text{-}8)$$

Now apply (10-6), (10-7) and (10-8) to the submachine gun M3. The following data apply to this gun:

projectile weight = 230 grains
charge weight = 7 grains
bolt weight = 2 pounds
muzzle velocity = 830 ft/sec
spring constant = .7 lb/in. (for each of 2 springs)
initial spring compression = 6 in.

Note: 1 lb = 7000 grains

If the gun itself remains stationary, and momentum in the closed system of gun, bolt, projectile and gases is conserved, then the momentum imparted to the bolt may be determined as follows:

(bolt) (projectile) (gases)
$$M_1 V_1 = M_2 V_2 + M_3 V_3$$

$$= \frac{230}{7000 \times 32.2} (830)$$

$$+ \frac{7}{7000 \times 32.2} (4700)$$

$$= 1 \text{ lb sec}$$

Note: the 4700 ft/sec value for the velocity of the gas is an empirical value for the effective velocity of the gas out of the muzzle.

The corresponding initial rearward velocity, v_0, may be obtained by dividing the momentum by the mass of the bolt

$$v_0 = \frac{1 \text{ lb sec}}{2/32.2} = 16.1 \text{ ft/sec}$$

This initial condition of rearward velocity, v_0, may also be obtained directly by the equation

$$v_0 = \frac{p\,V + 4700\,c}{W} = \frac{230 \times 830 + 4700 \times 7}{2 \times 7000}$$

$$= 16.1 \text{ ft/sec}$$

The undamped natural frequency of the system is,

$$\omega_n = \sqrt{\frac{k}{M}} = \sqrt{\frac{2 \times .7 \times 12 \times 32.2}{2}}$$

$$\omega_n = 16.4 \text{ rad/sec}$$

The maximum length of bolt recoil is then (from 10-6):

$$x_{max} - x_0 = \sqrt{x_0{}^2 + \frac{v_0{}^2}{\omega_n{}^2}} - x_0$$

$$= \sqrt{\frac{1^2}{2} + \frac{(16.1)^2}{(16.4)^2}} - \frac{1}{2}$$

$$= .6 \text{ ft or } 7.2 \text{ in.}$$

From (10-7) the time required for this length of recoil may be found,

$$T = \frac{\frac{\pi}{2} - \gamma}{\omega_n}$$

$$= \frac{\frac{\pi}{2} - \left[\tan^{-1}\left(\frac{x_0\,\omega_n}{v_0}\right)\right]}{\omega_n}$$

$$= \frac{\frac{\pi}{2} - .47}{16.4} = .067 \text{ sec}$$

and the cyclic rate of the gun is, therefore, $\frac{60}{2 \times .067}$, or 447 rounds per minute.

In order to illustrate the validity of this method of solving the differential equation of motion of a dynamic system for determination of response characteristics, results using energy techniques will be included. Obtaining results solely from energy considerations would be virtually impossible for more complex systems.

The maximum length of bolt recoil can be checked by the method of Chapter 10, Higdon and Stiles. The kinetic energy put into the bolt is:

$$KE = \frac{1}{2} M v_0{}^2$$

$$= \frac{1}{2} \frac{2}{32.2} (16.1)^2$$

$$= 8.05 \text{ ft-lb}$$

This must equal the energy input into the spring or the work done on the spring (neglecting friction). Referring to Figure 10-4, the work done on the spring can be seen to be:

$$\text{work} = (\text{average spring force}) \times (\text{recoil distance})$$

$$8.05 \text{ ft-lb} = k \left(\frac{x_0 + x_{max}}{2}\right) \times (x_{max} - x_0)$$

$$8.05 \text{ ft-lb} = (2 \times .7 \times 12) \times \left(\frac{.5 + x_{max}}{2}\right) \times (x_{max} - .5)$$

$$x_{max} = .6 \text{ ft or } 7.2 \text{ in.}$$

Further examination of Figure 10-4 shows that the maximum force transmitted to the shoulder of the firer is:

$$F_{max} = k \, x_{max} = 1.4 \times 12 \times 1.1 = 18.5 \text{ pounds}$$

The fact that this figure is very high for automatic small arms is one explanation for the tendency of this weapon to move when fired automatically for sustained bursts.

10-3 ANALOG COMPUTER SOLUTION

The equation of motion of the M3 bolt, neglecting friction, was derived in the preceding paragraph, and was found to be:

$$M \ddot{x} + k \, x = 0 \qquad (10\text{-}9)$$

with initial conditions at $t = 0$ of x_o and v_o. (10-9) may be conveniently written as:

$$\ddot{x} + \omega_n^2 \, x = 0. \qquad (10\text{-}10)$$

In the illustrative example, ω_n was found to be $16.4 \frac{\text{rad}}{\text{sec}}$, so (10-10) becomes:

$$\ddot{x} + 270 \, x = 0 \qquad (10\text{-}11)$$

To slow the solution down for visual observation of an oscilloscope or a pen recorder, it is desirable that the solution frequency be in the neighborhood of only $1 \frac{\text{rad}}{\text{sec}}$. To obtain this slower computer speed, simply divide ω_n by 20

to produce a new natural frequency of $.82 \frac{\text{rad}}{\text{sec}}$, remembering to multiply the measured cyclic rate by the same factor of 20 to return the solution to real time. Equation (10-11) now becomes:

$$\ddot{x} + \frac{270}{400} x = 0 \quad \text{or} \quad \ddot{x} = -.675 \, x \qquad (10\text{-}12)$$

The wiring schematic for the analog computer is shown in Figure 10-5. Refer to Chapter 3, Part 3, for the method of obtaining this diagram.

The computer solution simulates the action of the gun, enabling the designer to test the result of varying bolt weight, spring tension, or recoil velocity without actually building a weapon. If the designer wishes to study the effects of viscous friction, Figure 10-5 may be modified by the addition of a single resistance fed back across the first amplifier.
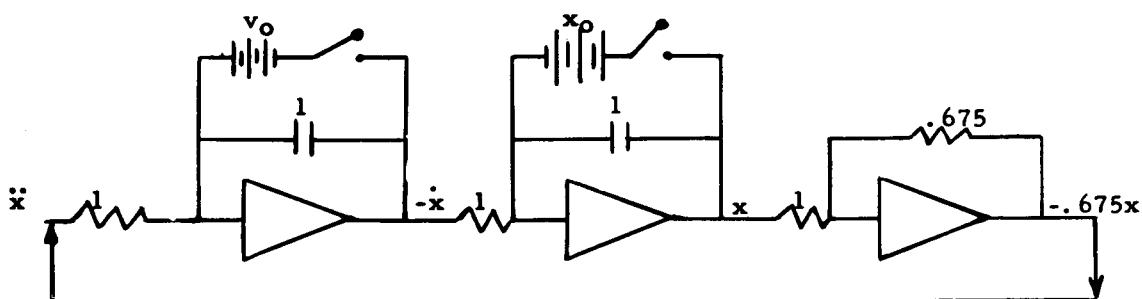

Fig. 10-5 Computer diagram for M3 bolt problem.

REFERENCES

1 Higdon and Stiles, *Engineering Mechanics,* Prentice-Hall, Inc., N.Y., 1949, Chapter 12.

2 Jensen, *Applied Engineering Mechanics,* McGraw-Hill Book Co., Inc., N.Y., 1947, Chapter 14.

3 Myklestad, *Fundamentals of Vibration Analysis,* McGraw-Hill Book Co., Inc., N.Y., 1956, Chapters 2, 3, and 4.

4 Timoshenko and Young, *Engineering Mechanics Dynamics,* McGraw-Hill Book Co., Inc., N.Y., 1937, Chapter 3.

CHAPTER 11

AMMUNITION AND WARHEADS

11-1 SMALL ARMS AMMUNITION—INTRODUCTION

In general, small arms include those weapons whose caliber (bore diameter across the lands) is not greater than 0.6 inch (caliber .60). This is an arbitrary figure, and in practice it is therefore difficult to draw a line between artillery and small arms. A usual distinguishing feature of small arms ammunition is the fact that it has no fuze, while most artillery ammunition is fuzed to achieve a particular terminal effect. Pistols, rifles, and machine guns, from caliber .22 through caliber .60, and shotguns, constitute the array of weapons usually thought of as small arms. Examples of specific weapons are the caliber .22 target rifle, the caliber .30 rifle and machine gun, the caliber .45 pistol and submachine gun. Each of these weapons has a variety of ammunition types designed for particular purposes, giving considerable versatility in performance.

11-2 HISTORY

A cartridge under our present military meaning is a complete round of ammunition for a firearm. The term cartridge comes to us from about the turn of the sixteenth century. The root word from which it comes is the Latin *carta* meaning paper. The term originated with the French in the word *cartouche,* meaning a roll of paper.

The earliest recorded use of a paper cartridge was in 1625 when Gustavus Adolphus issued them to his troops. The paper cartridge offered the advantage of quickly loading the weapon of the day with a uniform load. These cartridges were made by enclosing one or more bullets and a charge of powder into a roll of paper. The ends of the paper roll were tied with a string, or sealed with paste to keep the cartridge together. Grease was usually added to the paper to lubricate the bore and to retard water absorption by the powder. (Figure 11-1a).

Cartridges of this period were ignited through touch holes in the breech end of the barrel. Loading was from the muzzle requiring excessive allowance between diameter of the rifle ball and the bore diameter. In the British "Brown Bess" of 1800, the caliber was .753 in. while the bullet diameter was approximately .69 in. This flintlock weapon obtained a muzzle velocity of less than one thousand feet per second from a 500 grain round ball using some 70 grains of black powder. When fired at the shoulder level of a standing man, which was the method taught in European armies of the day, the ball struck the ground at about 125 yards. This range and accuracy was acceptable at that time, however, for battles between infantry units were commonly fought at 30 to 75 yards.

The paper cartridge, which was both combustible and self igniting, arrived on the scene with breech loading and was the immediate forerunner of our modern small arms round. Two examples of these rounds were those used in the German Zundnadelgewehr or needle gun (cal. .60 in.), and the French chassepot (cal. .43 in.). The needle cartridge was a paper-wrapped cartridge using a ball of smaller than bore diameter seated in a paper sabot (Figure 11-1b). The priming pellet was seated at the base of the sabot. The powder charge was behind the percussion pellet. The firing pin had to penetrate the entire charge to get to the primer and initiate the round. The chassepot round had the primer

Paper roll cartridge
(a)

Chassepot (right) and
the needle gun cartridge
(b)

Pin-fire cartridge
(c)

The .577 boxer cartridge
(d)

Fig. 11-1 Types of cartridges.
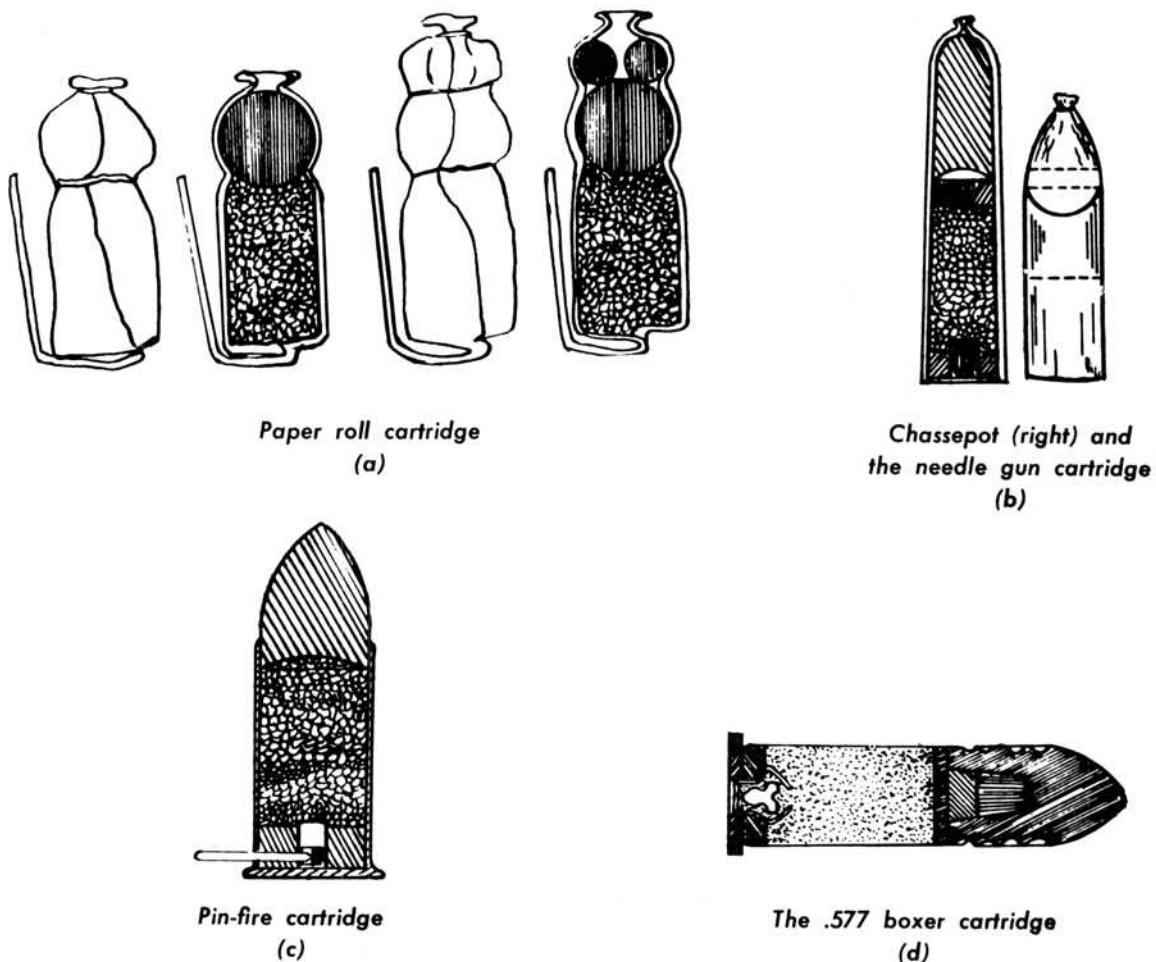
at the base of the cartridge (Figure 11-1b). Both rifles were bolt-action breech loaders and were used by the Germans and French in the Franco-Prussian War. In each instance, however, these weapons offered a poor solution to the problem of providing adequate forward and rearward obturation for after a number of discharges of the piece, the soldier tended to remove his face from the comb of the stock in order to prevent serious face burns from gas passing through the cartridge and breech. Accuracy was consequently greatly impaired; however, the superiority of these weapons over the muzzle loader was so pronounced that armies of this era, the mid 1860's, were soon seeking similar type shoulder pieces. By 1870 few first line troops in Europe carried muzzle loaders.

Weapons of the chassepot type used the percussion cap instead of a flint to secure initiation of the propellant. The principle by which the percussion cap was used had been developed and patented by the Reverend Alexander Forsyth, a Scottish clergyman, in 1807. By 1840 to 1845, this system of cartridge ignition was being used the world over. The percussion cap was the forerunner of our modern primer.

The first generally used complete cartridge as we know it today dates back to as early as 1836, when a Monsieur Le Faucheux of Paris made a pin-fire cartridge (Figure 11-1c). The case was of brass and paper and was of a form similar to that found in the modern shotgun shell. All-metal cases were also used. The pin, protruding

from the side, was struck, setting off the percussion cap and black powder propellant.

Rimfire cartridges in substantially their present form, were developed in the early to middle 1850's. Centerfire cartridges in forms similar to those we are now familiar with, were introduced in the Civil War period with a few earlier attempts at manufacture in the 1850's. It was not until 1866, however, that we had a separate primer centerfire cartridge which could be reloaded (Figure 11-1d). Colonel Boxer of the British Ordance Department is credited with this development. The modern cartridge, loaded with modern controlled burning, nonhygroscopic propellant, is but a refinement of these ideas of

a century or more ago.

It is of particular interest at this time to draw the attention of the reader to the marked reduction in caliber and bullet weight of small arms ammunition which has transpired over the years. The "Brown Bess" of 1800, having a caliber of .753 in. and firing a 500-grain round ball, is a graphic example of this when compared with our presently standard cal. .30 M2 cartridge and its 166-grain bullet. This trend has also included and in fact has been made possible by better ignition and propellant design, improved obturation, successful cartridge case design, achievement of higher muzzle velocities, and marked advances in metallurgy.

11-3 CARTRIDGE TERMINOLOGY

Much confusion in designating small arms ammunition can be eliminated by using correct terminology. This problem of terminology has been complicated by many different agencies naming their rounds. Civilian manufacturers all have their own trade names, the Navy has its own separate designations, and foreign armies and manufacturers lend their terminology to the large list. As an example of the above, one often hears of a .30-30 Savage or Winchester cartridge. The question immediately arises as to what the ".30-30" means. Actually it means that this cartridge was developed by Savage or Winchester, its caliber is .30 in. and that it contains 30 grains of propellant powder. The 30-06 cartridge for which the M1 rifle is chambered means a caliber of .30 in. with the round having been standardized in 1906. The 357 magnum is actually a cartridge of caliber .357 in. having a very large case and powder charge behind the bullet. It is often said that a 38 special cartridge may be fired in a revolver chambered for the 357

magnum cartridge. In this case the 38 bullet is actually a caliber of .357 in. The fit of the case is not good but the round may be fired in the 357 magnum. Many other such designations exist, and unless an individual is an expert in the field, he may be confused easily.

The military terminology system is simple and direct. It merely describes the complete round according to its function and model number. For example, the nomenclature "Cartridge, Armor Piercing, Cal. .30 M2" indicates that this round is designed for armor penetration and is the second model of its series.

To avoid confusion in making components of the complete small arms round, the word cartridge is used to designate the complete round, being made up of the bullet which is the small arms projectile; the cartridge case; the propellent powder; and the primer. Other important terms which are applied to small arms cartridges are shown in Figure 11-2. These terms will be referred to throughout this chapter.

11-4 COMPONENTS OF THE COMPLETE ROUND

Most cartridges are made up of a cartridge case, a primer to initiate the explosive train, a propellent powder, and a bullet. The design and manufacture of each of these components is

intricate and requires extensive engineering and production planning. When one stops to consider that Company X can manufacture a primer no bigger than a tack and ship it to Company
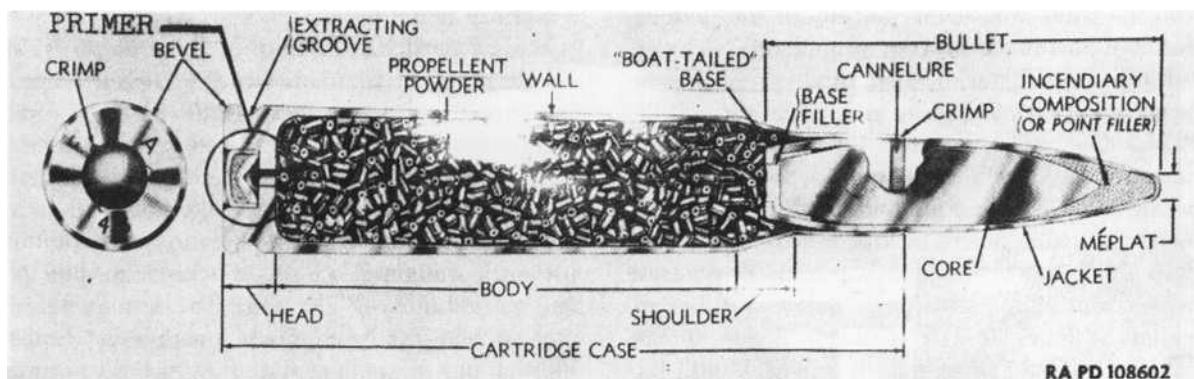
Fig. 11-2 Terminology of complete small arms round (Cartridge, Armor Piercing Incendiary, Caliber .50, M8).

Y for assembly into a pre-drilled hole in the cartridge case bottom, and have all primers guaranteed to fit any cartridge case, it is apparent that fits and tolerances must be exacting. It is

this manufacturing care and exactness which guarantees the uniform functioning of each cartridge from round, to round. Each of the cartridge components will be considered below and its most important features discussed.

11-4.1   THE CARTRIDGE CASE

Cartridge cases are either of the centerfire or rimfire type. From the standpoint of shape they are straight, straight taper, or bottleneck. Figure 11-3 illustrates the types of cartridge cases normally encountered.

The cartridge case has three functions: It is the means by which the other components (primer, propelling charge, and bullet) are assembled into a unit. It also provides a waterproof container for the propelling charge. When the cartridge is fired, it prevents the escape of gases to the rear as the thin side walls of the case are forced against the walls of the chamber by the pressure. This process of sealing by expansion is termed obturation.

In the assembly of the cartridge the primer is pressed into the primer pocket and staked or crimped (only primers in military cartridges are staked, civilian primers are not), the joint then being sealed by a drop of shellac or lacquer to keep out moisture. The cartridge case is next loaded with a charge of propellent powder, the inside of the neck is coated with lacquer or some other waterproofing compound; the bullet inserted; and the mouth of the case crimped into

the cannelure of the bullet. For cal. .30 carbine and cal. .45 cartridges the mouth of the case is not crimped; the bullet is held in place by its tight fit in the case. In some revolver cartridges a cannelure prevents the bullet from being seated too deeply.

Rounds thus assembled have an exceptionally long storage life. Ammunition remaining from World War I was, in so far as it was available, generally acceptable for use in World War II. Many small arms rounds have been fired after fifty years of storage with excellent ballistic performance.

11-4.2   THE PRIMER

Percussion primers of the boxer type are in general use. This standard primer is crimped into the primer pocket in the head of centerfire cartridge cases and consists of a soft metal cup, a priming or percussion composition, a disk of shellacked manila paper, and an anvil (Figure 11-4). A blow from the firing pin on the primer cap compresses the priming composition between the cup and the anvil. The priming mixture, being sensitive to stab action, burns and
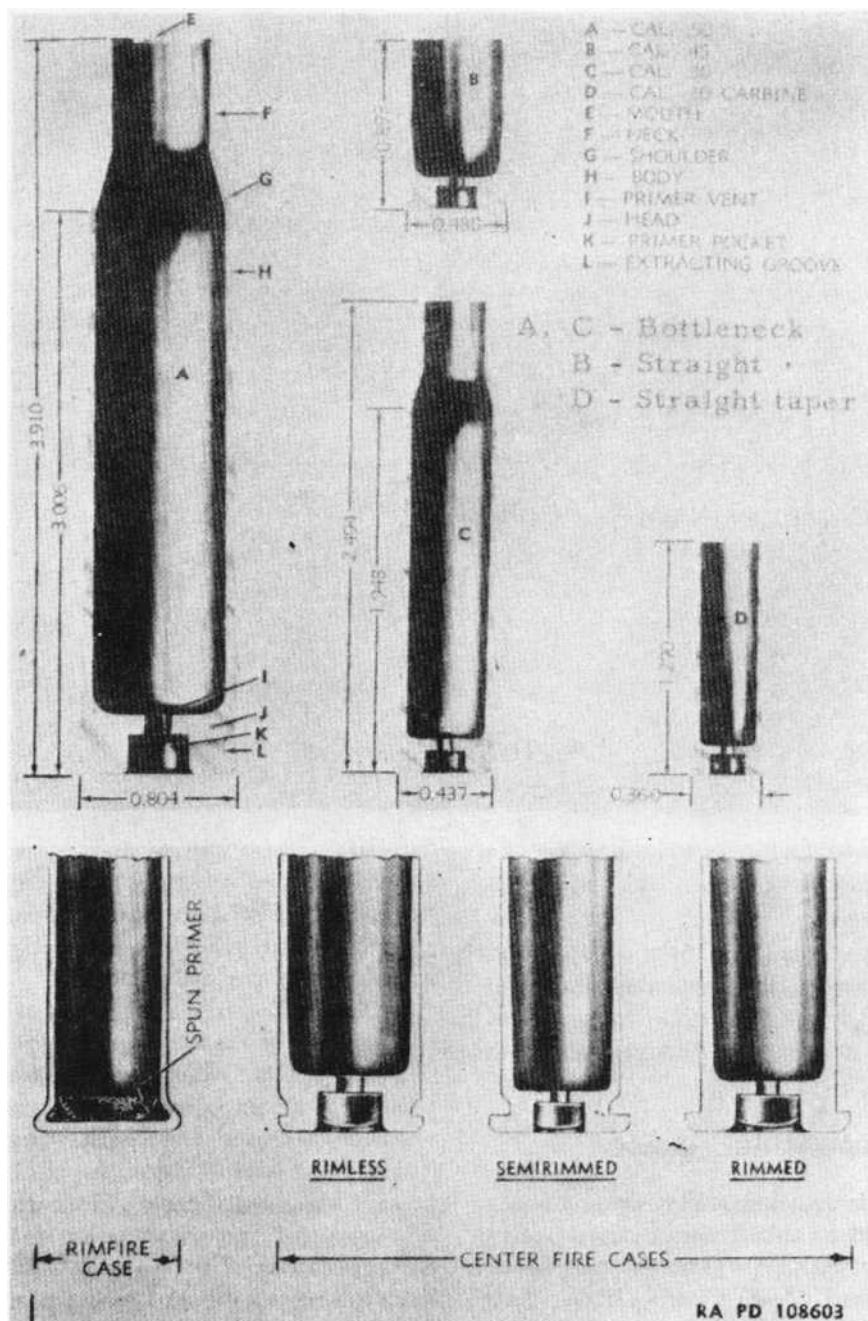
Fig. 11-3 Types of cartridge cases.

A. Components of a primer.

B. Primer assembled.
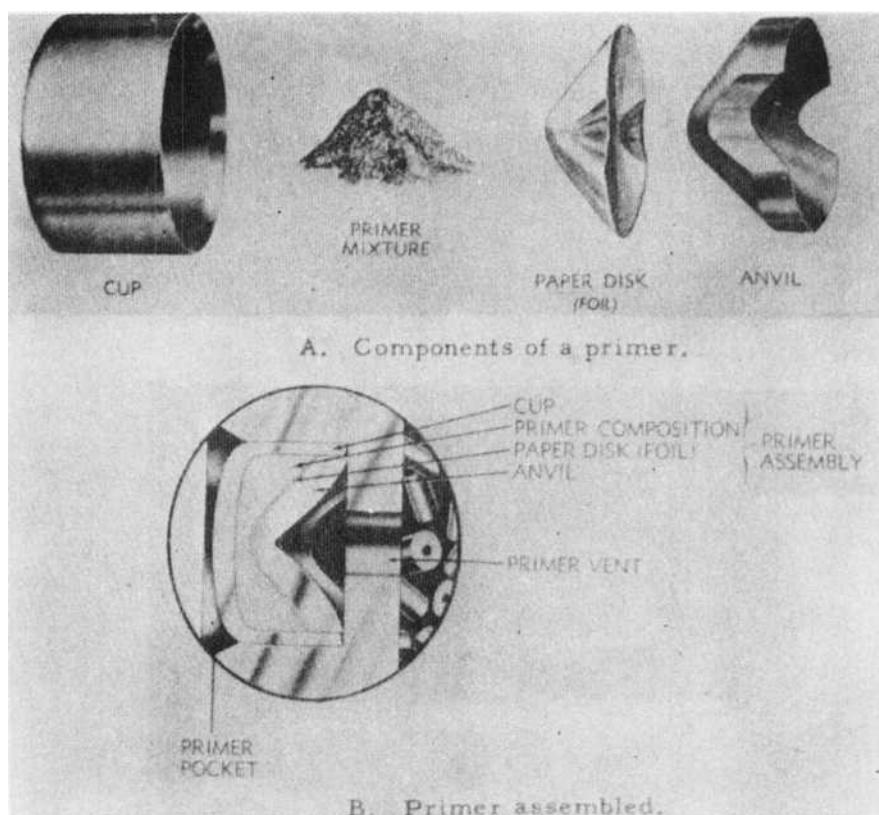
Fig. 11-4 The primer.

emits a hot flame which passes through the vents in the anvil and cartridge case, and ignites the propelling charge.

The priming composition in the cup is held in place and protected from moisture and electrolytic action by a paper disk. The brass anvil is inserted last, completing the assembly of this type of primer.

11-4.3 THE PROPELLING CHARGE

Small arms propellent powder is single-base or double-base powder in the form of cord, spheres (T65, NATO cartridge) or single perforated grains coated with DNT and glazed with graphite. In mass production loading it is loaded loosely in the case by machine. The grains are very small and therefore subject to more rapid deterioration at high temperatures than grains of artillery powder. It is interesting to note that the powder pressures developed by small arms powders are generally much greater than those

found in larger weapons. For example, maximum powder pressure of the caliber .30 AP round in the M1 rifle is 50,000 pounds per square inch, while that for the high explosive shell M71 in the 90-mm gun is 38,000 psi.

The weight of the charge is not constant. It is adjusted for each propellant lot to give the required bullet velocity with chamber pressure within the limits prescribed for the weapon in which it is fired.. The charge for cal. .30 cartridges is about 50 grains (437.5 grains per ounce) while that for cal. .50 cartridges is about 240 grains. The corresponding velocities at 78 feet are about 2700 and 2900 ft/sec,. respectively. The density of loading is usually about 0.9. This is very high when compared to a density of loading from 0.3 to 0.7 for artillery rounds.

11-4.4 THE BULLET

The modern small arms bullet is an accurately made projectile designed for a specific purpose

such as penetration of armor, incendiary effect, or antipersonnel effect. It must function at the target at all temperatures between −65 and 170°F, and it must withstand storage under all conditions. It has no fuze, rotating band, or bourrelet, but otherwise the same design principles apply to both artillery and small arms projectiles. There are two types of bullets in use in military small arms cartridges: the lead bullet, and the jacketed bullet. The currently known ball bullet derives its name from early lead ball-shaped slugs; today, however, lead bullets are used only in cal. .22 ammunition and in some revolver cartridges.

Lead bullets are not satisfactory for use where high velocities are desired because their softness causes deformation by setback, thus harming exterior ballistic performance. In addition, lead bullets may be damaged by loading mechanisms of automatic weapons, and may cause jamming of such weapons. Accordingly, the great proportion of military bullets are metal jacketed. The bullet consists of a core covered by a gilding metal (90% copper, 10% zinc) jacket, a gilding metal clad steel jacket, or a copper plated steel jacket. A cannelure is cut or rolled in the jacket to provide a recess into which the mouth of the case may be crimped during assembly. The cannelure also serves to hold the jacket and core together more firmly.

The diameter of a jacketed bullet is usually about .001 inches greater than the bore diameter between the grooves. This is to provide a tight gas seal and to allow the jacket to be gripped properly as the bullet is rotated by rifling in the barrel.

The body of the bullet is cylindrical. The nose may be round as in the carbine, pistol, and revolver bullets, or ogival (curved taper) as in all service rifle and machine gun bullets. The length of the ogive or taper for cal. .30 and .50 bullets is approximately 2.5 calibers. The base may be square or boattailed (Figure 11-5). The boattail is highly effective in lessening drag up to the speed of sound, and gives some advantage up to a velocity of 2900 feet per second. Beyond 2900 feet per second the boattail has no appreciable advantage, and accordingly the additional

cost is not warranted.

(a) Ball. The metal jacketed ball bullets contain a core of antimony-lead alloy, except the cal. .50 bullet wherein the core is of soft steel in order to insure similar ballistic properties for ball and armor-piercing cartridges. Caliber .30 carbine and cal. .45 ball bullets are similar, differing essentially in diameter. Unlike other ball bullets, the cal. .50 bullet is boattailed and contains a point filler of hardened lead. This type of bullet is now used for target practice only (Figure 11-5).

(b) Armor piercing. Armor piercing bullets contain a core of hardened steel, either a tungsten-chromium steel or a manganese-molybdenum steel. The cal. .30 armor piercing bullet has a point filler of lead and a gilding metal base filler between the core and the jacket, whereas the cal. .50 armor piercing bullet has only an antimony-lead alloy point filler. Both bullets have smooth cannelures cut into the jacket for crimping of the cartridge case. AP bullets should penetrate homogeneous armor to a depth of 1.5 to 2 times the caliber of the core. This bullet has replaced ball ammunition for combat because of its ability to penetrate armor without deforming, better sectional density, and better wind bucking and ricochet characteristics (Figure 11-5).

(c) Armor piercing incendiary. Armor piercing incendiary bullets have hardened steel cores and instead of a point filler of metal, have one consisting of an incendiary mixture of barium nitrate and magnesium powder (Figure 11-5).

(d) Armor piercing incendiary tracer. These bullets are similar to the armor piercing incendiary bullets but also have a tracer composition in the base end of the bullet for fire control (Figure 11-5).

(e) Incendiary. Incendiary bullets contain a core of incendiary mixture. An antimony-lead
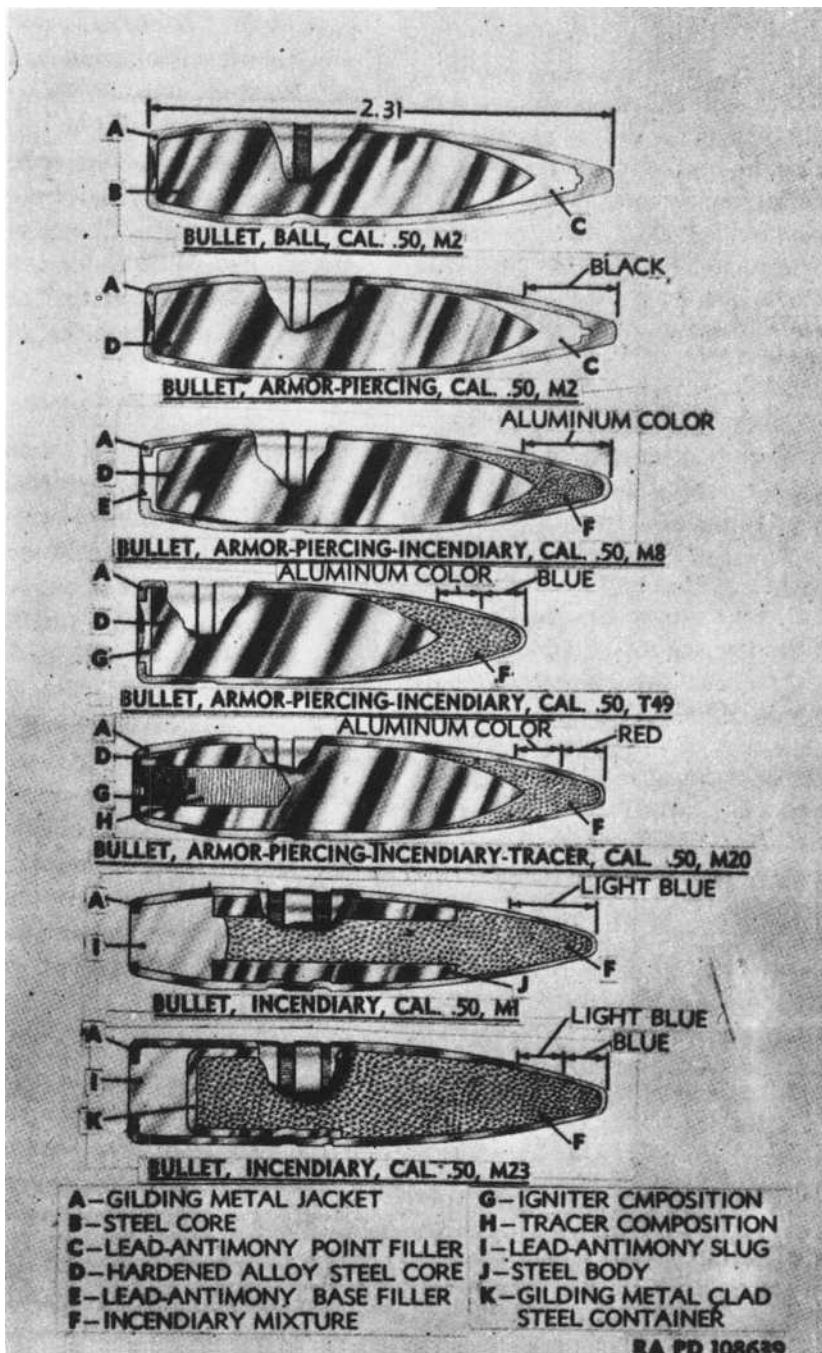
Fig. 11-5 Types of cal. .50 bullets.

alloy slug is present at the base end of the bullet. A hollow, steel, cylindrical body or a clad-steel container may be inserted within the jacket and before the base slug (Figure 11-5).

(f) Tracer. Tracer bullets (Figure 11-6) contain an antimony-lead alloy slug in the forward position, and in the rear a tracer composition including strontium peroxide, strontium nitrate, magnesium, and other ingredients. They all have square bases. An igniter composition is also present and is ignited by the burning propellent gases. The igniter then ignites the tracer composition. The red-tipped M1 tracer bullets are visible starting at the muzzle; the orange tipped tracer bullets have a dim trace for a short distance from the muzzle and a bright trace thereafter; and the maroon tipped bullets have a comparatively long trace. A special headlight tracer bullet has a very bright trace when viewed from the front; its tracer charge is a fast burning igniter composition placed in the base. This so-called headlight round was developed to create the impression on the enemy that he was being fired on by weapons larger than those actually being used.
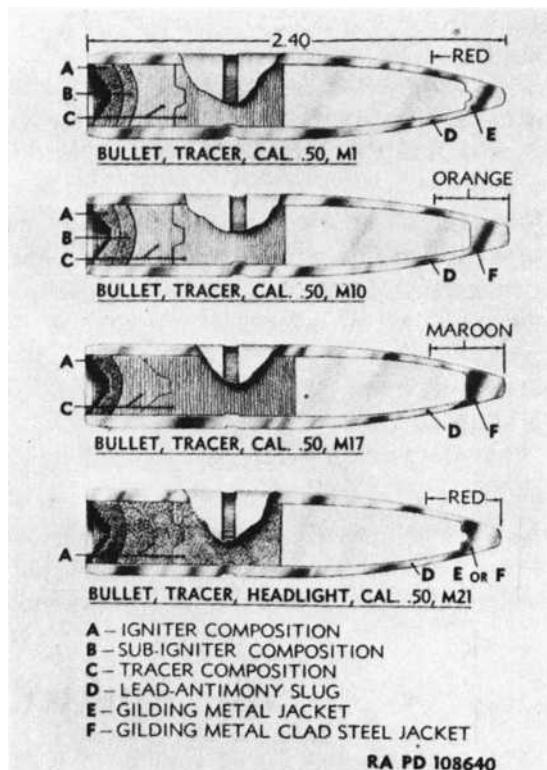
Fig. 11-6 Cal. .50 tracer bullets.

11-5 GRADES AND GRADING

Because of mass production methods, variations in the quality of small arms ammunition are bound to occur from lot to lot, although requirements and specifications for acceptance are very rigid. For example, ammunition used in remote control aircraft machine guns must have uniform characteristics from round to round to insure uniform feeding. If a malfunction occurred it could not be corrected in the air and the weapon would be out of action. The best ammunition available, therefore, must be used for these aircraft machine guns. Some lots manufactured which do not pass the aircraft tests may still be suitable for use in ground machine guns and rifles where a possible malfunction could be corrected easily. A system of grades and grading is necessary to provide the best ammunition for use in the most critical weapon and to relegate lower grades to more rugged weapons. The grades that have been established for small arms are given below, the most critical as to performance requirements being listed first.

USE	GRADE	
Aircraft machine gun	AC	(cal. .50)
Aircraft machine gun or rifle	AC or R	(cal. .30)
Rifle	R	(cal. .30)
Ground machine gun	MG	(cal. .50 and cal. .30)
Unserviceable	3	(cal. .50 and cal. .30)

Lot numbers that have been established for each lot of small arms ammunition are instrumental in controlling the use of ammunition.

Basically a lot number indicates that each cartridge within that lot has been manufactured with identical components, i.e., from the same lot, and that there should be very little difference in functioning within the lot. Figure 11-7 shows a small arms container with the lot number (EC L-8000) painted on it in addition to other important information. These lot numbers also serve as an administrative control. The Chief of Ordnance periodically publishes to the field units a list showing the grading of each lot number.

The problem of maintaining ammunition in storage at acceptable standards for service is an expensive and laborious one. Periodically, samples of each lot are tested, and if they fail to meet rigid requirements the lot is downgraded.
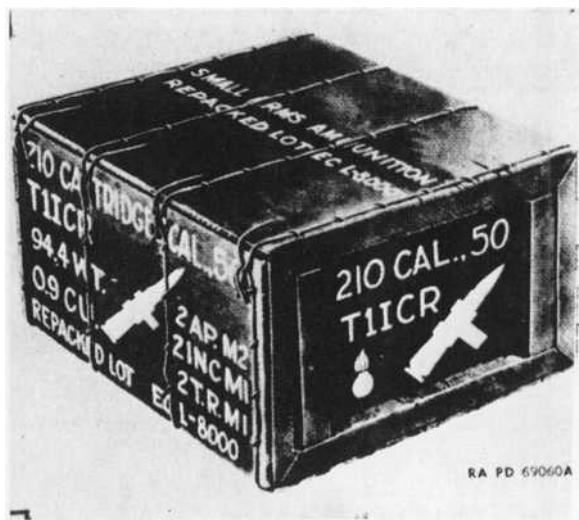
Fig. 11-7 Ammunition box showing markings.

11-6 ARTILLERY AMMUNITION—HISTORY

The first recorded use of cannon in warfare dates from about 1350. The projectiles generally were stone balls and, although iron and lead shot came into use at the beginning of the fifteenth century, the stone projectile did not pass completely out of the picture until the beginning of the nineteenth century. Some of those employed in the bronze guns of the time were very large, up to 25 inches in diameter.

The early iron projectiles were solid spherical shot. Bar shot and chain shot, consisting of two iron balls connected by a bar or chain, were developed and used for cutting the masts and rigging of vessels. Chilled iron shot was employed when the first wrought iron armor came into use.

The hollow spherical shot or shell, filled with a bursting charge of gun powder or with incendiary material, was developed from the solid shot. Another kind of projectile which came into use in the eighteenth century was the case shot, consisting of a number of smaller projectiles in a case or envelope. The three principal types were grape, canister, and spherical case or shrapnel. The first two contained no explosive charge and were designed to break up in the gun or at the muzzle; the last had a bursting charge and a fuze.

Use of spherical projectiles continued until the period of our Civil War when the elongated form, cylindrical with pointed nose, was adopted for use in cannon as it had been previously for hand arms. For a given caliber of weapon, this change of form enabled the use of much heavier projectiles of increased capacity, and resulted in the attainment of increased range and accuracy of fire. It necessitated, however, provision of means for imparting the necessary rotation to secure stability in flight. In the muzzle loading cannon of the period, firing cast iron projectiles, special devices for producing rotation were developed.

The bore of the Whitworth gun, invented in 1857, was a twisted prism of hexagonal cross section (Figure 11-8). The projectile was fashioned with plane surfaces to correspond. For use in rifled cannon, various means were adopted to attain rotation as illustrated in Figure 11-9.

In the studded type, protruding studs were fitted into the helical grooves of the rifling as the projectile was inserted in the muzzle. In the eureka and butler projectiles the parts were of soft brass and, in firing, were expanded outward into the rifling. Projectiles of these types permitted considerable escape of powder gas past them, with resulting decrease in velocity and accuracy.
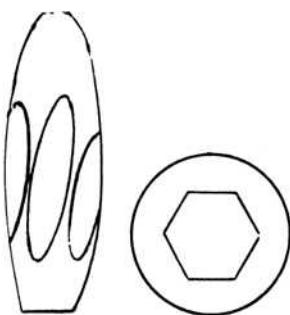
Fig. 11-8 The projectile and bore of Whitworth gun, 1857.
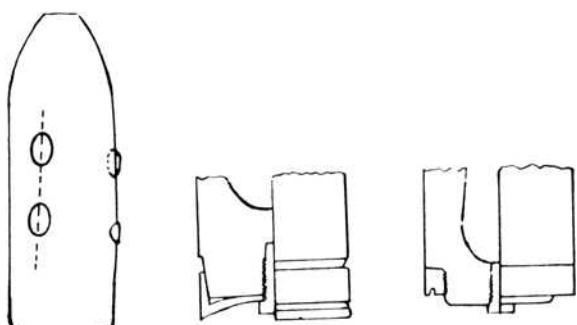
Fig. 11-9 Various means attempted to obtain rotation.

The introduction of rifling in cannon was followed shortly by the development of effective methods of breech closure, permitting employment of breech loading. The use of progressive burning propellants and the adoption of smokeless powders of definite chemical composition permitted the attainment of higher velocities with lower pressures. Developments in metallurgy and in gun manufacture resulted in weapons of greater strength and power. These factors greatly influenced projectile development. The use of steel gave added strength and permitted the inclusion of larger bursting charges of powerful new high explosives. Increases in velocity brought about improvements in shape and form designed to decrease retardation in flight due to air resistance, thereby increasing range and accuracy. Ammunition development was facilitated by the evolution of new and improved means of testing and determining ballistic effects.

11-7 COMPLETE ARTILLERY ROUNDS

In general, artillery ammunition includes ammunition for weapons greater than caliber .60, except rockets. The weapons concerned are guns (both standard and recoilless), howitzers, and mortars. A complete round of artillery ammunition comprises all of the components necessary to fire the weapon once. Complete rounds of artillery ammunition are known as fixed, semifixed, separate loading, and separated, in accordance with the manner in which they are loaded into the weapon (Figure 11-10).

11-7.1 FIXED AMMUNITION

Fixed ammunition is comparable to the typical small arms round, in that the projectile is permanently fastened to the cartridge case and is loaded into the weapon as a single piece. The propelling charge is not adjustable, and if the projectile becomes loosened from the cartridge case before firing the round is considered unserviceable. Cartridge case and projectile are normally crimped rigidly together, with the propelling charge loaded loosely into the cartridge case.

11-7.2 SEMIFIXED AMMUNITION

Semifixed ammunition is characterized by the loose fit of the cartridge case over the projectile so that the propelling charge is accessible for adjustment for zone firing. Like fixed ammunition, it is loaded into the weapon as a unit. The propelling charge is divided into sections, each containing propellant powder assembled in a bag. To adjust the charge, the projectile is lifted from the cartridge case, the sections or increments not required are removed, and the projectile is reassembled to the cartridge case.
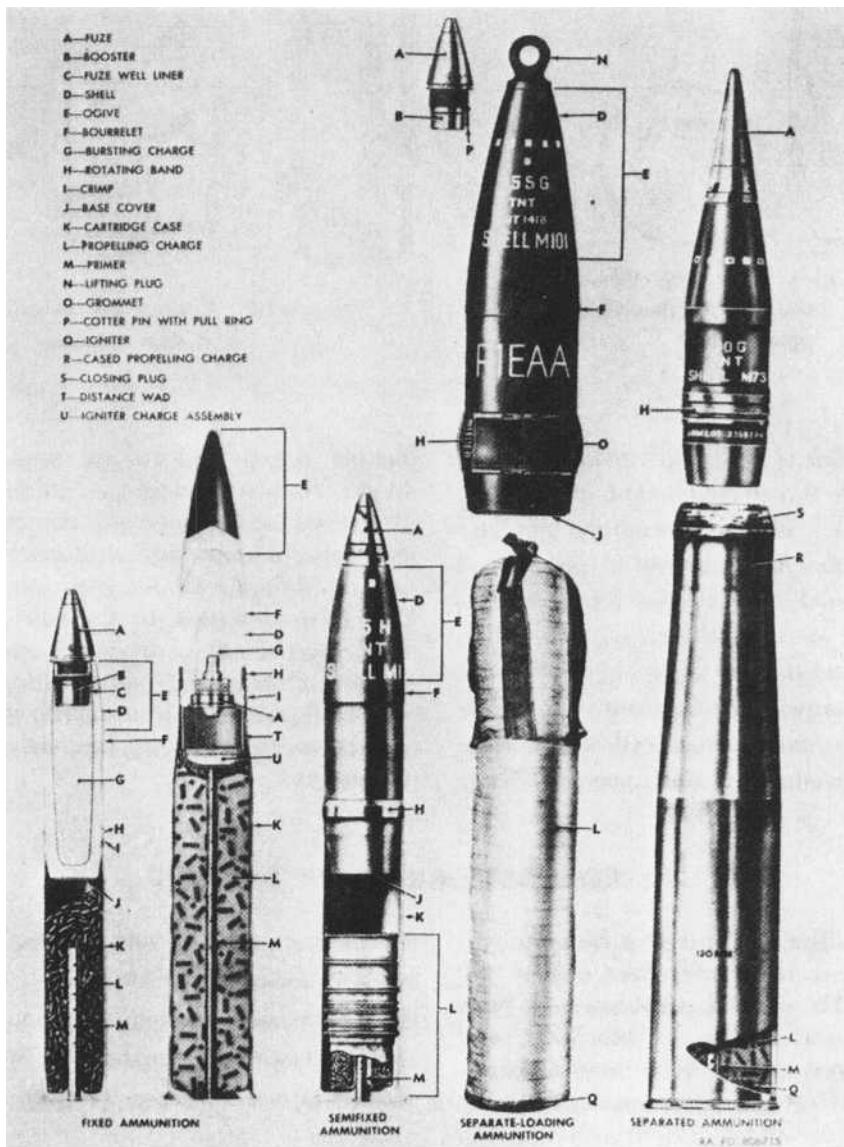
Fig. 11-10 Complete rounds of artillery ammunition.

11-7.3 SEPARATE LOADING AMMUNITION

Separate loading ammunition components (projectile, propelling charge, and primer) are loaded into the weapon separately. First, the projectile is inserted into the breech and rammed home so that the rotating band seats in the forc-ing cone; second, the propelling charge, consisting of one or more cylindrical cloth bags, is placed in the powder chamber immediately to the rear of the projectile; and third, after the breechblock has been closed and locked behind the charge, the primer is inserted into the firing mechanism.

11-7.4 SEPARATED AMMUNITION

Separated ammunition is a special type of separate loading ammunition. The propelling charge is fixed and is contained in a cartridge case, which is closed at the forward end by a cork or plastic plug. The projectile does not fit into the cartridge case and is loaded into the cannon separately. This type of ammunition facilitates rapid loading by breaking long, heavy rounds into two parts. Ammunition for the 120-mm antiaircraft gun is of this type.

11-8 COMPONENTS OF THE COMPLETE ROUND

11-8.1 PRIMERS

The artillery ammunition primer is designed to ignite the propelling charge. It consists essentially of a small arms primer to which a small charge of black powder (igniter charge) has been attached. The primer cap and the black powder charge are usually assembled in a metal tube. When used with fixed, semifixed, and separated ammunition, this tube is force fitted into the base of the cartridge case at the time of manufacture. With separate loading ammunition the primer is inserted by hand into the firing lock or firing mechanism of the cannon as a final step in loading. Historically, artillery primers have been classified according to the method by which they are fired as percussion, electric, combination, percussion-electric, and friction. By far the most common primer in actual use today is the percussion type.

(a) Percussion primer. This type of primer, fired by a blow of the firing pin, is generally used in all artillery ammunition (see Figure 11-11). The primers used in cartridge cases contain sufficient black powder to ignite properly the propellant in the cartridge case. Those used with separate loading propelling charges contain only enough black powder to ignite a black powder igniter charge attached to the propelling charge.

(b) Electric primer (see Figure 11-12). This type of primer is fired by the heat generated when an electric current passes through a resistance wire or other element embedded in primer mixture. It is used currently in certain types of 20-mm ammunition for aircraft cannon.

11-8.2 CARTRIDGE CASES

Fixed, semifixed, and separated ammunition all employ a cartridge case as one component of the complete round. In fixed and semifixed ammunition, the cartridge case performs the same functions as small arms cartridge cases, i.e., container for the propellant; obturating device; and means of assembling the components of the complete round into a unit for ease of loading. In separated ammunition, the cartridge case does not perform the third of these functions.

Most cartridge cases are made of drawn brass or steel. A new development is the spiral wrap cartridge case. It is assembled from three steel pieces consisting of a forged base and a spirally wrapped body held together by a stamped collar. The body is made by rolling a preformed trapezoid-shaped steel sheet in the same way a sheet of paper is rolled to form a hollow cylinder. The design greatly reduces the amount of equipment needed to manufacture cartridge cases and will result in a unit cost only about ⅔ of the cost of the drawn case.

PRIMER, PERCUSSION, M1B1A2   RA PD 80872A

75 and 105 MM - HOWITZER
120 MM - GUN
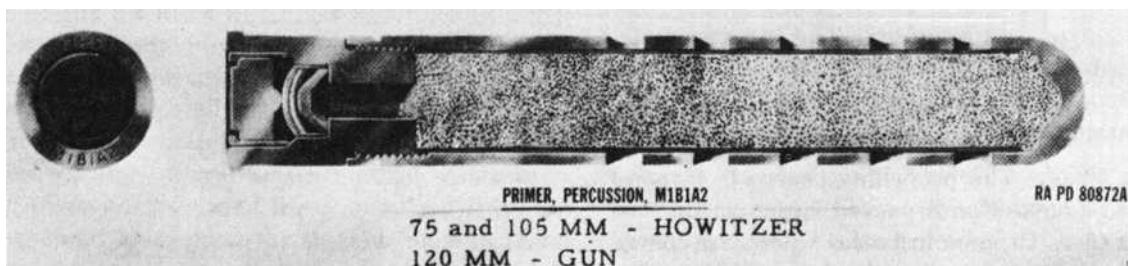
Fig. 11-11 Percussion primer.

COATED WITH
INSULATING
ENAMEL

ELECTRIC PRIMER, M30

A—Igniter charge
(primer charge)
B—Insulator

C—Gun cotton
D—Contact or
ignition wire

E—Closing cup
F—Pressed black
powder pellets
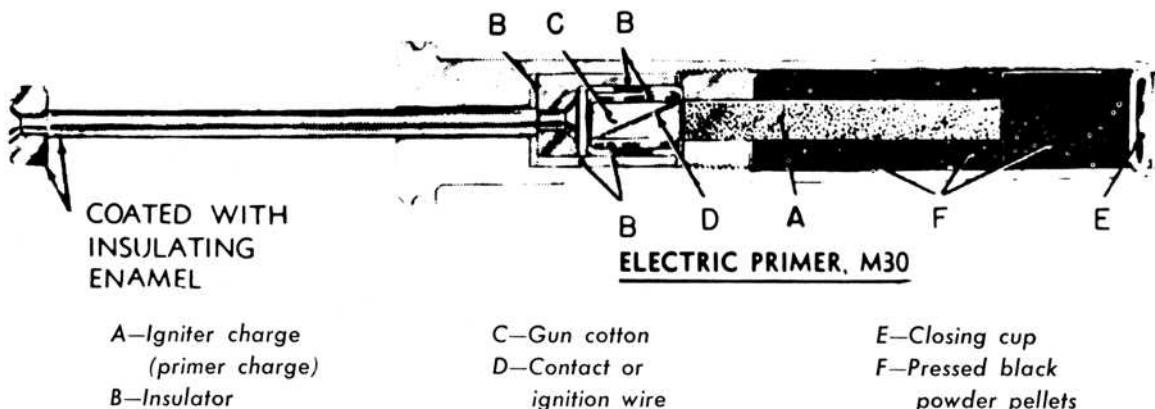
Fig. 11-12 Electric primer.

11-8.3 PROPELLING CHARGES

Artillery propelling charges consist of a propellent powder and an igniter charge of black powder assembled in a suitable cartridge case, cloth bag, or both. In fixed and semifixed rounds, the igniter charge of black powder is present in the artillery primer. In separated ammunition an auxiliary igniter charge is placed around the primer or on the distance wadding to insure proper ignition of the propellant. In separate loading rounds the igniter charge is assembled to an igniter bag sewed to the base end of the propelling charge and in some cases also forming a core running through the center of the propelling charge bag. Cartridge igniter pads are made of closely woven silk to prevent the black powder from sifting through. Cloth of current manufacture used for the igniter charge is dyed red to indicate the presence of the black powder igniter. The propelling charge is assembled with the artillery round in a manner determined by the type of ammunition, that is, fixed, semifixed, separated, and separate loading (Figure 11-10). The various charges used are discussed below.

(a) Fixed and semifixed. The cartridge case, made of drawn brass or steel, serves as the container for the propelling charge of fixed and semifixed ammunition.

(1) Fixed. The propelling charge in a round of fixed ammunition is packed loosely in the cartridge case. In some instances where the charge does not fill the case completely, a spacer or distance wadding, usually a cardboard disk and cylinder, is inserted in the neck of the cartridge case between the powder charge and the base of the projectile.

(2) Semifixed. Semifixed ammunition differs from fixed ammunition in that the cartridge case is not crimped to the projectile, but is a loose fit so that it can be removed and the propelling charge adjusted to vary the range; therefore, the charge is contained in bags so that one or more of these bags can be removed and the rest replaced. Each increment is numbered, the base charge being numbered 1.

(b) Separated ammunition. This propelling charge is contained in a cartridge case, together with the primer. The charge consists of propellent powder, loosely loaded in a brass cartridge case which is closed by a cork or plastic plug. As previously stated, this permits rapid loading. In the case of 120-mm ammunition (Figure 11-10), the assembled cartridge case is used to ram the projectile into the weapon.

(c) Separate loading. Cloth bags form a suitable and convenient means of containing the smokeless powder charges in separate loading ammunition. Cartridge bag cloth was formerly made of silk. Bags made of cotton or rayon are now used almost universally to replace silk. Only certain ash-free grades of these fabrics are suitable; otherwise there might be smoldering fragments left in the bore of the cannon after firing.

Separate loading propelling charges are usually divided into several bags, or increments, so that different weights of charge can be chosen by the gun crew. This permits increased flexibility in operation; that is, there will be several
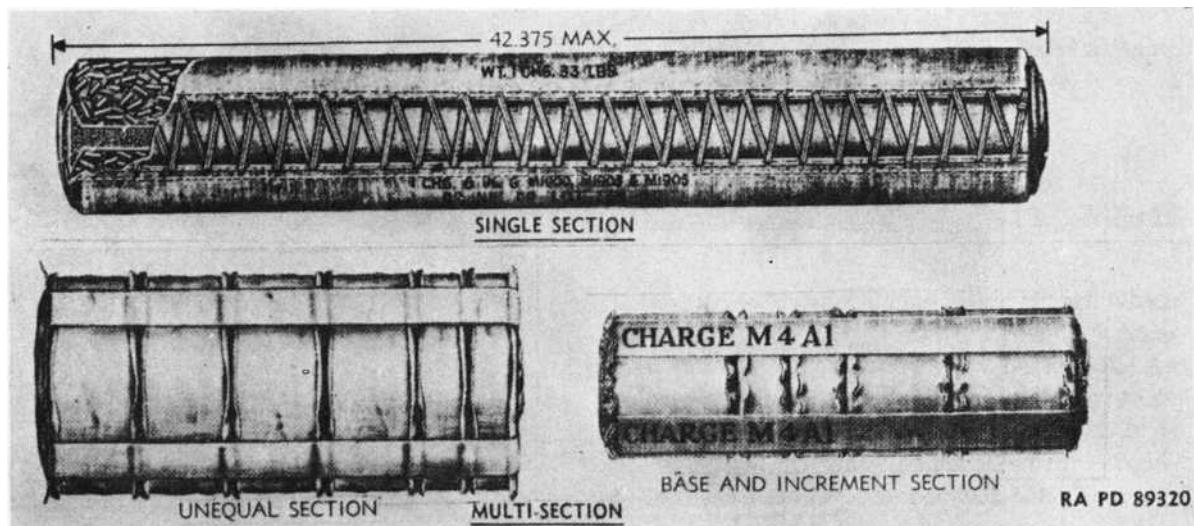
Fig. 11-13 Separate-loading charges.
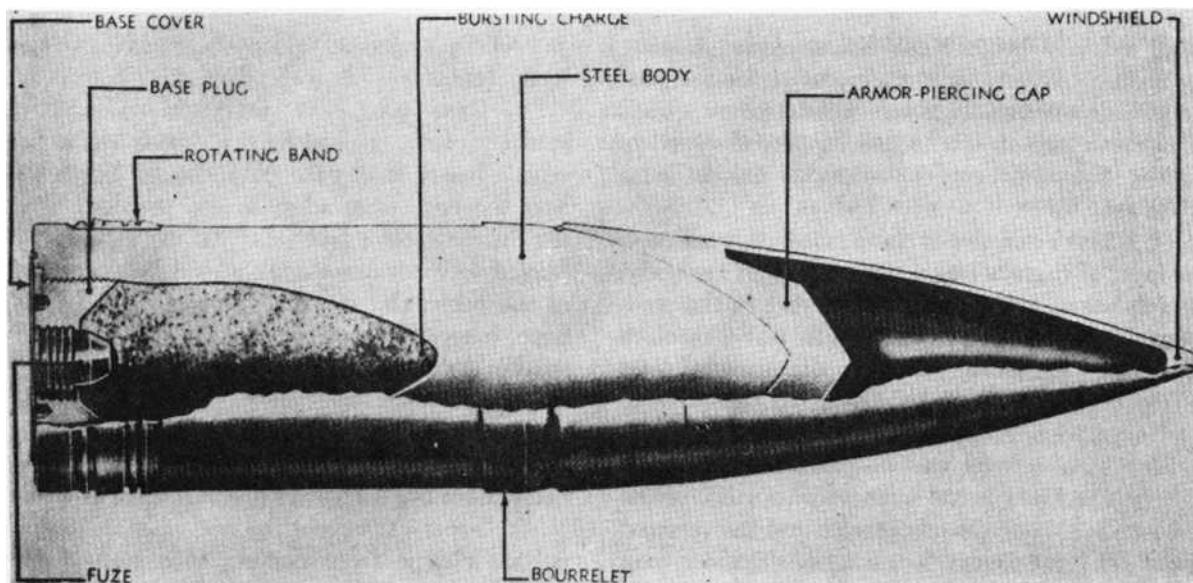
Fig. 11-14 Armor piercing capped shell, showing principal parts.

elevations which can be used to obtain a given range. Thus, plunging fire, grazing fire (for ricochet action), or intermediate angles of fall can be obtained at the same range simply by altering the weight of propellant and changing weapon elevation accordingly.

11-8.4 PROJECTILES—GENERAL CHARACTERISTICS

Figure 11-14 shows a sectionalized view of an artillery projectile with its component parts

labeled. The principal characteristic differences among the various projectiles are:

(a) Ogive. The curved portion of the projectile from the bourrelet to the point is called the ogive. It is normally defined as a segment of an arc of a circle whose center is outside of the projectile. The radius of the ogive is usually expressed in calibers. It influences the flight of the projectile with a small radius used for low velocity projectiles and a long radius used for
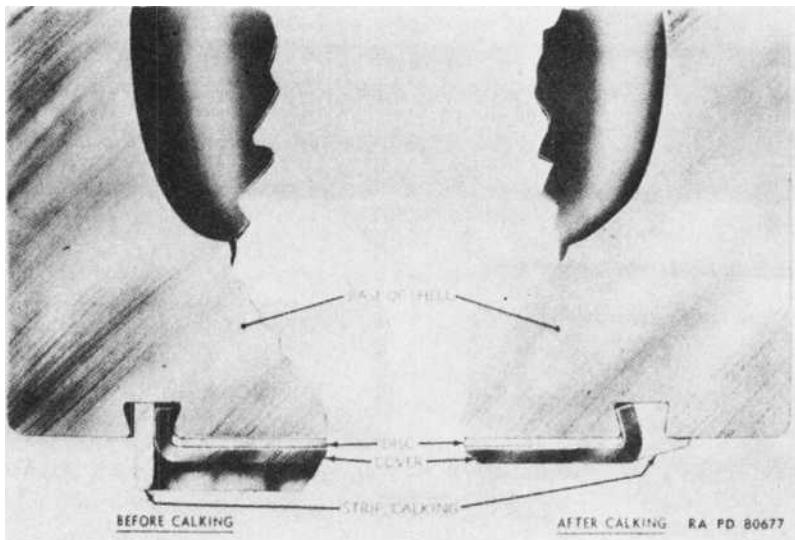
Fig. 11-15 Base cover.

high velocity projectiles. Since armor piercing projectiles have a short radius of ogive for purposes of penetration, a windshield, often called a ballistic cap or false ogive, is placed over the armor piercing head to improve the ballistic qualities.

(b) The bourrelet is the accurately machined surface, of slightly larger diameter than the body, which bears on the lands of the bore of the weapon. It centers the projectile in its travel through the bore. Generally it is at the forward end of the body, but it may extend from the ogive to the boattailed base. Some projectiles of large caliber have a front and rear bourrelet.

(c) The body is the cylindrical portion of the projectile between the bourrelet and the rotating band. It is machined to a smaller diameter than the bourrelet to reduce the surface in contact with the lands of the bore. Only the bourrelet and rotating band bear on the lands.

(d) The base may be either tapered (boattailed) or cylindrical (square). Whether or not a boattail is used depends upon the velocity intended for the major part of the useful trajectory. For example, boattails will not be found on HVAP ammunition, which is intended to travel at more than 3000 feet per second over its useful trajectory. However, they will be found on most high explosive rounds, where high striking velocity is not generally considered a requirement of the round, and where the major

part of the trajectory is usually covered at a velocity much less than the 2900 feet per second.

(e) Base plug. To facilitate manufacture, armor piercing projectiles are closed at the base with a heavy steel base plug. In the larger calibers the base plug adapter also provides a seat for the base plug and fuze. In the smaller calibers, if an explosive charge is loaded in the cavity of the projectile, the base plug is replaced by a base fuze. If no explosive is present in the smaller caliber projectile the base plug contains the tracer element.

(f) Base cover (Figure 11-15). 20-mm projectiles and projectiles of 75-mm or larger caliber containing high explosive are provided with a base cover to prevent the hot gases of the propelling charge from coming into contact with the explosive filler of the projectile through joints or flaws in the metal of the base. The base cover consists of a thin metal disk which may be calked, crimped, or welded to the base of the shell. Small caliber and medium caliber armor piercing projectiles with high explosive filler and base fuzes are not ordinarily provided with base covers.

(g) The rotating band is a cylindrical ring of comparatively soft material, usually copper or gilding metal (sintered iron has also been successfully used) pressed into a knurled or roughened groove near the base of the projectile. On some HVAP projectiles, however, the band is
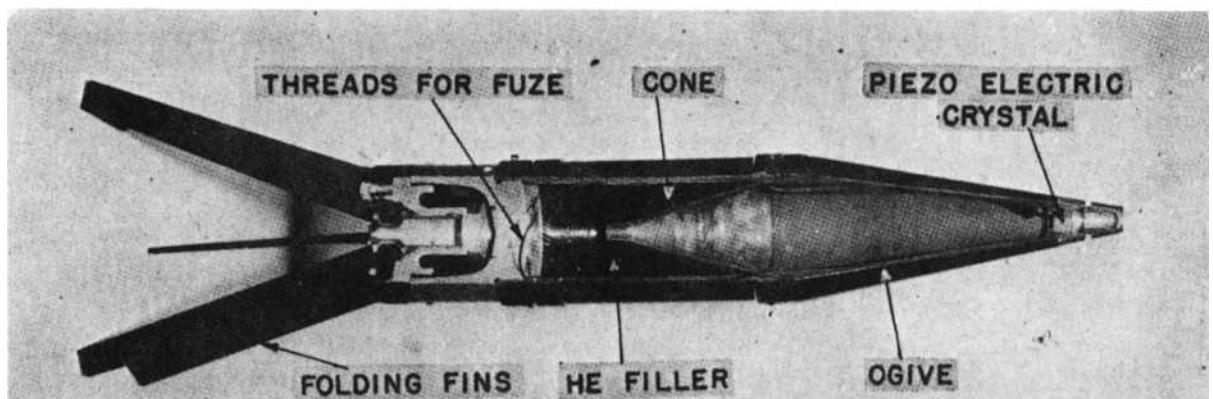
Fig. 11-17 High explosive antitank shell.

steel and is an integral part of the base. The rotating band affords a snug seat for the projectile in the forcing cone of the weapon and centers the base in the bore. As the projectile moves forward the soft rotating band is engraved by the lands of the bore. Because of compression and cutting of the band, excess metal flows toward the rear. This flow of metal is taken up by grooves cut in the rotating band. Since the rifling of the weapon is helical, the engraving of the band imparts rotation to the moving projectile. The rotating band also prevents the escape of the propellent gases forward of the projectile by completely filling the grooves of the rifling. Rotating bands are made relatively narrow for low velocities and wider for high velocities.

(h) Tracer. For observation of fire some projectiles are equipped with a tracer element in the base of the projectile. In most smaller caliber antiaircraft shells the tracer is used to ignite the filler and destroy the shell should it miss the target. Such a tracer is called shell destroying (SD). Tracer compositions are similar to small arms tracer compositions.

(i) Armor piercing cap. A differentially hardened cap used only with armor-piercing projectiles.

11-8.5 PROJECTILE TYPES

(a) High explosive (H.E.) shells (Figure 11-16) made of common forged steel, have comparatively thin walls and a large bursting charge of high explosive. They are used against personnel and materiel targets, producing blast or mining effect, or both, and fragmentation at the target. They may be fitted with either a time or impact fuze or a concrete piercing fuze, according to type of action desired.

(b) The high explosive antitank (H.E.,A.T.) shell, often called the shaped charge or hollow charge shell, is a special type containing a high explosive charge for use against armor plate (see Figure 11-17). Chapter 10, Part 2 presents a comprehensive explanation of the action of these projectiles.

(c) Armor piercing projectiles defeat armor by piercing it because of their kinetic energy. A

BURSTER CASING   BURSTER CHARGE   SLEEVE   ADAPTER

BURSTER TYPE CHEMICAL SHELL

—18 84—

BASE PLUG   CANISTER   IGNITER   SMOKE MIXTURE

BLACK POWDER EXPELLING CHARGE
BASE EJECTION SMOKE SHELL

DELAY PELLETS

SPACING DISC

PELLET CHARGE   SMOKE MIXTURE
BASE-IGNITION SMOKE SHELL

RA PD 97762
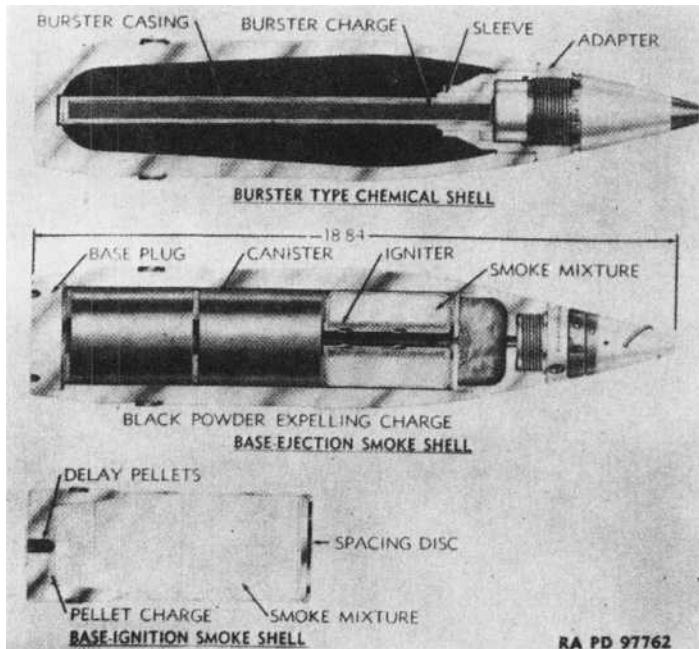
Fig. 11-18 Typical chemical projectiles.

detailed discussion of this type of projectile appears in Chapter 10, Part 2.

(d) Hypervelocity armor piercing shot (HVAP) (see Figure 10-17) is described in Chapter 10, Part 2.

(e) High explosive plastic projectiles (H.E.P.). (See Par. 10-21, Part 2.)

(f) Chemical shells may be classified according to the method of expelling the charge (Figure 11-18): burster, base ejection (B.E.), and base ignition (BI).

(1) The burster type is similar to high explosive shell except for the type of filler and the absence of a base cover. An explosive charge, termed a burster, and located centrally in the shell, is used to break the shell body and aid in dispersion of the chemical filler.

(2) Base ejection shells which are set to function in flight do not have a burster but have an expelling charge of black powder adjacent to the time fuze. This expelling charge, when ignited by the fuze, ignites the smoke mixture in the canisters, strips the threads of the base plug, and forces the canisters from the base of the shell.

(3) Base ignition (base emission) smoke shells have no burster or expelling charge. The smoke mixture is ignited by the propelling charge through a hole in the base of the projectile. Shells of early manufacture have a low melting point fusible metal plug in the base hole, while shells of late manufacture have delay pellets of black powder. The action of the delay pellet prevents disclosure of the gun position by the smoke.

(g) The illuminating shell (Figure 11-19) contains a parachute and an illuminant assembly which are ejected by an expelling charge adjacent to the time fuze in a manner similar to base ejection smoke shell. The illuminant, suspended by the parachute, burns and lights a target area.

(h) Canisters consist of a light metal case filled with steel balls or cylindrical pellets. They contain no explosive (Figure 11-20) and are fired point blank for effect against personnel. Centrifugal force and air pressure cause the projectile to break apart upon leaving the muzzle of the cannon, and the balls or pellets scatter in the manner of a shotgun charge. Canisters are not to be confused with the famous shrapnel round of World War I. Shrapnel is a time fuzed round which functions at a set time after firing, causing

TIME FUZE

DESCENT WHILE CENTER WIRE IS ATTACHED TO ILLUMINANT

CENTER WIRE

EXPELLING CHARGE

BAFFLE PLATES
SURFACE CHARGE
IGNITION CHARGE
FIRING CHARGE
RELEASE SLEEVE SOLDERED ONTO CENTER WIRE
CENTER WIRE
CENTER WIRE TUBE
CAN
ILLUMINANT CHARGE

SPLIT WASHER
SWIVEL PIN
COMPRESSION PAD
SHROUD PLATE
SWIVEL PIN NUTS

PARACHUTE SHROUDS
PARACHUTE

DESCENT AFTER CENTER WIRE IS RELEASED

CENTER WIRE

PARACHUTE RETAINER SPRING
SHEAR PIN
BASE PLUG
TWIST PIN

RA PD 97760

Fig. 11-19 Illuminating shell.
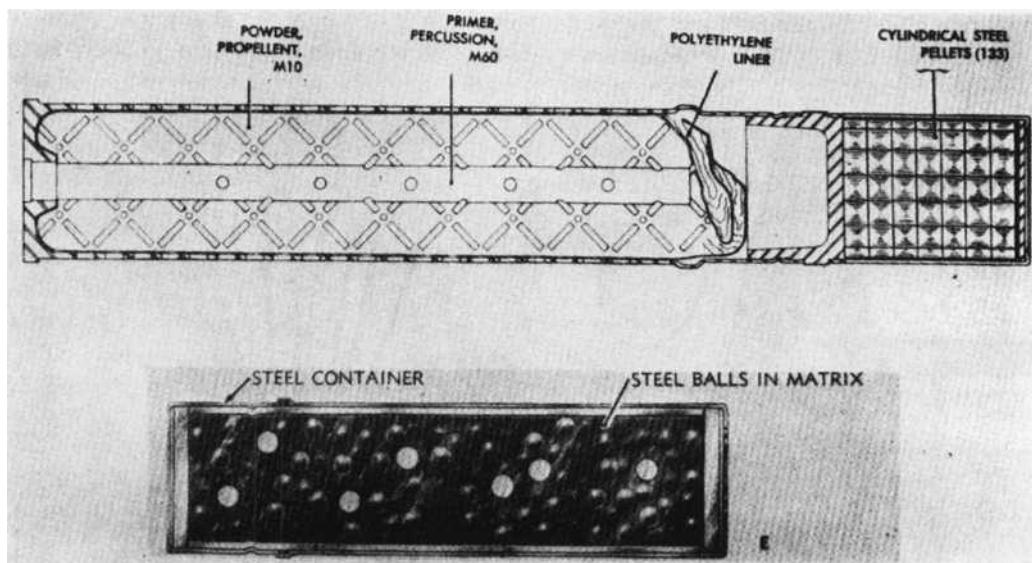
Fig. 11-20 Canisters: top, 57-mm recoilless rifle; bottom, 37-mm.

metal balls to be shot forward from a projectile-like body. New development in canisters include changes in the design and arrangement of the missiles within the container, and in the location at which the container releases the missiles. One type, for use in the 90-mm gun, consists of a heavy base with rotating band, and a thin steel cylindrical forward section filled with stacked steel cylindrical pellets. The cylindrical forward section has four slits, 90° apart, which weakens the walls sufficiently to facilitate opening the canister when it leaves the muzzle of the weapon. This is an improvement over the type shown in the lower view of Figure 11-20, which often broke up while in the gun tube and damaged the bore.

11-9 MORTAR AMMUNITION—COMPLETE ROUNDS

Mortars are used where high angles of fire are desired for plunging fire behind hills or into trenches, emplacements, or foxholes. The muzzle velocities and ranges of mortars are less than those of guns and howitzers, but because of their extreme simplicity, mobility, and dependability they are used extensively by infantry units. Mortars allow ammunition of gun and howitzer caliber to be fired almost immediately after establishment of a beachhead.

Most mortars are smooth bore and muzzle loaded (see Figures 11-21 and 11-22), although the 4.2-in. mortar is a rifled, muzzle loaded weapon. Muzzle loaded rounds must be complete as a unit so that when they are dropped tail down into the weapon, impact with the firing
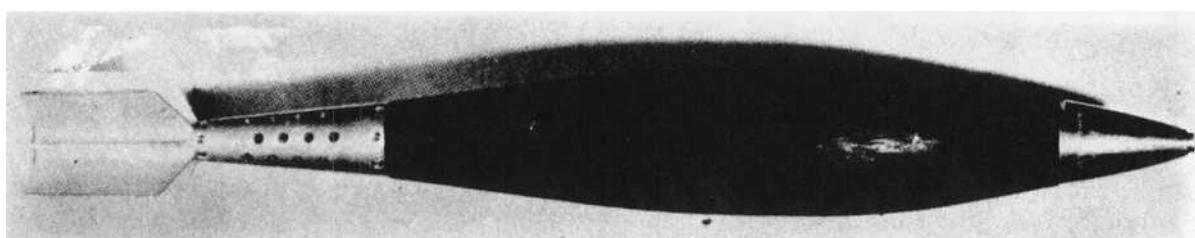
Fig. 11-21 Typical round of mortar ammunition.

pin is all that is needed to set off the propelling charge. Smooth bore rounds must have fins to stabilize them since rotation is absent.

Mortar ammunition is being redesigned in the U.S. Army with the objective of obtaining the optimum ballistic shape. Figure 11-21 shows the shape of a typical mortar shell of the new design. It is probable that in the future all mortar ammunition will have a similar shape.

Mortar projectiles are usually lighter in construction than artillery projectiles because the chamber pressures and setback forces are much less. Smooth bore projectiles have no rotating band, and they contact the bore at two or three places, one being a series of machined bands called the gas check bands, and another being the outside portion of the fins. The gas check area is near the front of the projectile.

The principal types of mortar projectiles are high explosive, chemical smoke, and illuminating. They are all point fuzed. The low muzzle velocity, high trajectory, and lack of extreme accuracy preclude the use of mortar armor piercing projectiles.

In general, mortar ammunition has an adjustable propelling charge to permit firing at various ranges or zones of fire. The propellent increments are usually of double-base powder sealed in individual, plastic type packages, and are attached to the fin shaft or within the fin blades. An ignition cartridge, comparable to an artillery primer, is inserted in the base end of the fin shaft. The assembly of the ignition cartridge and the propellent increments make up the required propelling charge. Because the complete round is loaded into the mortar as a unit and provision is made for adjusting the propelling charge, ammunition of this type comes within the classification of semifixed ammunition.
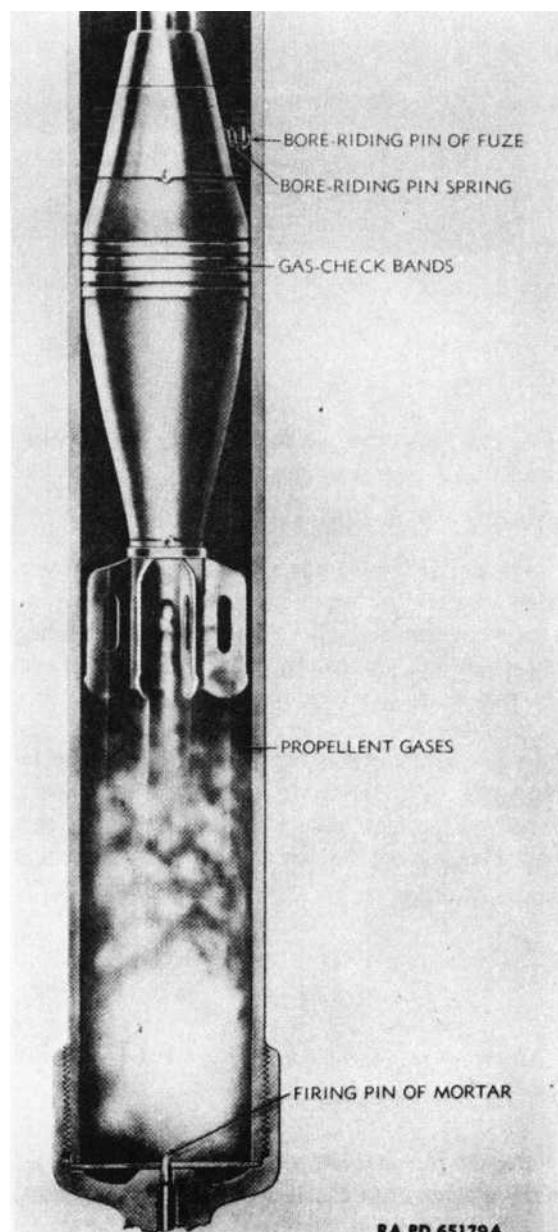
Fig. 11-22   60-mm mortar shell being fired.

11-10   RECOILLESS RIFLE AMMUNITION—COMPLETE ROUND

Recoilless rifle ammunition (Figure 11-23) differs from conventional artillery ammunition in the following features: rotating band, cartridge case, and propelling charge.

11-10.1   ROTATING BAND

Recoilless rifle projectiles have preengraved rotating bands in order to reduce performance variations from round to round; to reduce weight of the gun tube by elimination of engraving stresses in the tube; and to reduce the possibility of recoil in the weapon. The use of preengraved bands decreases the speed with which recoilless

WEAPON SYSTEMS AND COMPONENTS
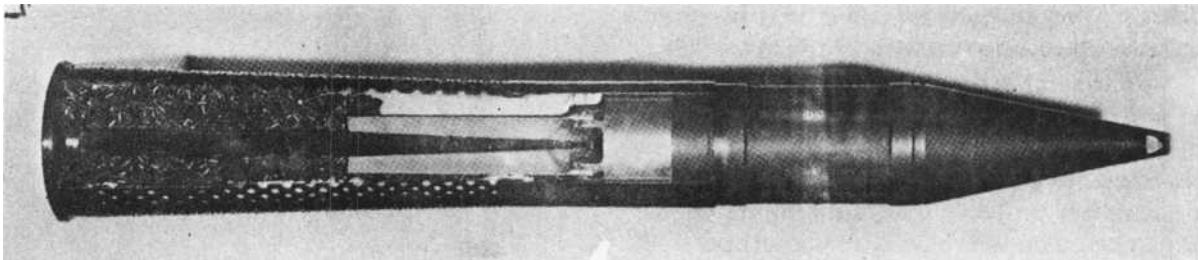
Fig. 11-23 Recoilless rifle round.

rifles can be loaded, as the rotating band must be carefully engaged in the rifling.

11-10.2 CARTRIDGE CASE

The cartridge case is of steel and is perforated with a large number of holes. These holes permit escape of the propellent gases into the enlarged chamber and thence through venturi orifices in the breech to produce the force opposing recoil. In conventional artillery ammunition the unperforated case protects the propelling charge from moisture. Protection in the recoilless round is achieved through use of a moisture-proof plastic bag conforming to the inside diameter of the case. This bag is consumed at the time the round is fired with little effect on ballistic performance.

11-10.3 PROPELLING CHARGE

The propellant is a single-base powder of the same general type as that used in conventional artillery ammunition but is employed in much greater quantity for a given projectile weight, caliber, and muzzle velocity. This is understandable in view of the fact that in addition to propelling the projectile, it must offset the tendency of the system to recoil. Higher effective gas velocities would add to the relative efficiency of the propellant, but would also increase the blast.

11-11 BOMBS—INTRODUCTION

Bombs for aircraft, as known today, are largely a development of the last two decades. Although bombs were used in World War I, the size, accuracy and terminal ballistics at that time were such that their military value was limited almost entirely to psychological and nuisance effects. Between wars, some development work was done on bombs, but only in the late 1930's did progress become rapid. Stimulated by World War II, the aircraft bomb quickly became a major weapon of destruction, and in the final tally for that war, bombs accounted for more killing, wounding, and property destruction than any other type of weapon.

Bombs are essentially aimable containers of explosive or other material which are designed to function at particular times and under predetermined conditions. In some instances, the container is constructed so that it will produce a particular fragmentation effect at the target.

A typical bomb consists of four main parts (see Figure 11-24):

(a) The bomb body, with its explosive, chemical, or other content.

(b) A fin assembly to stabilize its flight.

(c) An arming wire assembly.

(d) A fuze or fuzes to explode the bomb at the proper moment.

Usually these parts are assembled into a complete round just before being loaded into the bomb bays or other carrying devices of aircraft.

CHAPTER 12

FUZES

12-1 INTRODUCTION

A fuze is a device for igniting, detonating, or releasing the charge or warhead of a missile and causing it to do the type of work for which it is designed. Fuzes may perform their function upon impact, at a certain predetermined time, at a specific distance from the target, or under various other conditions. A fuze is but a small part of a complete weapon system, but unless the functioning of the fuze is exactly as intended, the entire effect of the missile may be lost.

The fuze designer must bear in mind the following characteristics as he plans a fuze:

(a) Certainty of action.
(b) Safety in handling and use.
(c) Freedom from deterioration in storage.
(d) Simplicity in design and construction.
(e) Strength to withstand the forces of firing or launching.
(f) Compactness.
(g) Streamlining for good ballistics.
(h) Ease of manufacture and loading.
(i) Reasonable economy in manufacture.

Some of these characteristics are conflicting; for instance, the addition of safety features may greatly complicate the problem of design and increase the cost of manufacture.

Additionally, each of the characteristics listed becomes more or less critical depending upon the type of missile being launched. Thus, compactness is essential for the fuze of an artillery projectile, yet becomes less important for large missiles where space is not so restricted. Furthermore, simplicity is often sacrificed for reliability when the missile is to carry a very large and expensive warhead.

Compact fuzes such as those for artillery shells, small rockets, and mortars, must perform the same functions as larger fuzes, such as are found in large guided missiles. Essentially, they must initiate detonation at the optimum time, while assuring that detonation does not occur prematurely. Since the fuze must be safe when launched, the fuze designer must take advantage of forces or effects available during and after launch to prepare the fuze for firing and to activate it.

In general, modern fuzes consist of a connected series (train) of small explosive charges, together with a device for initiating the action of the first charge in the train. In the functioning of a fuze, each charge by its action initiates that of the next charge in the train, the final charge in the fuze causing the detonation of the bursting charge in the missile.

12-2 CLASSIFICATION OF FUZES

When considering types of action, or manner of functioning, fuzes may be classified as:

Time
Impact
Proximity
Hydrostatic
Chemical delay
Ambient

12-2.1 TIME FUZES

In time fuzes the time delay is initiated upon launch of the missile. The time element is obtained by use of either a powder train of black powder or by a mechanical device similar to a watch mechanism. In spin stabilized rounds, the mechanical type has largely replaced the powder train type because of its greater accuracy. The

rate of burning of a powder train is affected by moisture, density of the air, and the degree of compression of the powder in the train due to setback; factors to which the mechanical fuze is relatively insensitive. Time fuzes are designed for use against aircraft and for air bursts against certain types of ground targets.

12-2.2 IMPACT FUZES

Impact fuzes are designed to function upon impact with the target or at some short time thereafter. In this type the time delay, if any, is measured from the instant of impact. The following list describes the types of impact fuzes:

(a) Superquick. This type is designed to burst the missile immediately upon impact and before it has penetrated, resulting in very little cratering and a maximum effect above ground. The period of time from impact until detonation of the bursting charge for superquick fuzes is on the order of 100 microseconds. The firing pin is driven directly into the primer by the force of impact: They are used on chemical shells and on H.E. shells where the target is above the ground (wire, personnel, or light materiel).

(b) Supersensitive. This type is the same as the superquick, except that it is designed to function upon impact with a very light target, such as an aircraft wing. These fuzes are always point fuzes. The firing pin is driven directly into the primer by impact just as it is with superquick fuzes.

(c) Non-delay. This type is designed to burst the missile before complete penetration of the target occurs. A small crater is obtained, most of the effect being above ground. Non-delay fuzes do not act as quickly as superquick fuzes. This is because the firing pin is of the inertia type and is carried forward against the primer by the force of inertia (setforward force) on impact. The functioning delay is on the order of 500 microseconds. They are used on H.E. missiles against materiel targets and lightly fortified positions. In World War II, H.E., A.T. (shaped charge) projectiles, such as the round for the 105-mm howitzer were used. H.E., A.T. rounds are now point initiated, base detonating (P.I., B.D.).

(d) Delay. This type is designed to burst the missile in 05-.25 seconds after impact. It includes a primer assembly of the non-delay type together with a delay powder pellet between the primer and detonator. These fuzes are used on all A.P., H.E. missiles and on H.E. missiles when some penetration of the target is desired, such as against earth, lightly constructed emplacements, etc. They are also used to obtain ricochet action of shell when firing against personnel. On AP missiles the fuze is always in the base, but for other missiles it may be either a base or a point fuze or both.

(e) Selective superquick or delay. This type is designed so that the fuze may be set for either superquick or delay action, thus giving versatility of performance. It is always a point fuze.

(f) Piezoelectric fuzes. For applications where extremely rapid action is required (e.g., high velocity H. E., A.T. rounds), a fuze depending for its initiation upon a piezoelectric crystal is used. Contact with the target deforms the crystal, delivering current to an electric detonator and starting the fuze action.

12-2.3 PROXIMITY FUZES

The proximity fuze was one of the spectacular developments of World War II. This fuze is actually a combination of radio broadcasting and receiving station. The waves, which are constantly being broadcast by the fuze at a set frequency, are reflected back from the target and picked up by the receiving set in the fuze. This fuze functions when it comes within proper proximity to any target capable of reflecting its waves. Various other proximity devices such as photoelectric sensers, have been attempted, but without notable success to date in this country.

12-2.4 HYDROSTATIC FUZES

Hydrostatic fuzes are employed in depth bombs for underwater demolition work. The fuzes work on the principle of a bellows or diaphragm which expands owing to increase in water pressure as the bomb sinks, and thus counteracts the force exerted by a spring. When the spring force is overcome, the firing pin is released and driven against the primer by spring action, the action really being that of a cocked firing pin.

12-2.5 CHEMICAL FUZES

Chemical long delay fuzes are employed in aircraft bombs to produce detonation from 1

hour to 144 hours (6 days) after release. Delay is obtained through employment of a chemical combination of alcohol and acetone to soften a celluloid collar thus releasing a cocked firing pin. This type of fuze is particularly responsive to heat and cold. High temperatures shorten the time delay and low temperatures retard it. The design of these fuzes usually incorporates anti-withdrawal devices to prevent enemy bomb disposal personnel from disarming the bomb during the delay interval.

12-2.6 AMBIENT FUZES

These fuzes make use of ambient conditions existing above the surface to sense altitude above target. The most probable condition to be used is air pressure, which is accurately known as a function of altitude. Other possible conditions which might be measured are the earth's electrostatic or magnetic fields.

12-3 PRINCIPLES OF FUZE DESIGN

A fuze must be so designed that it will not only assure certainty of functioning at the proper time or place, but will also assure certainty of not functioning prematurely, with resultant damage to the launching device and crew. To obtain these ends, the fuze designer has available certain forces with which to work, depending upon the type of ammunition for which he is designing a fuze. The forces available include the following: (Figure 12-1)

(a) Setback. The force of inertia or resistance to the extreme acceleration of the projectile in the bore of a gun or after launch until burnout in the case of a rocket. It is the same force which flings an automobile driver back against the seat when he suddenly accelerates the vehicle. Setback is available from the instant the projectile starts to move until it stops accelerating. It is maximum for tube-launched projectiles where pressure is maximum $(F = Ma)$.
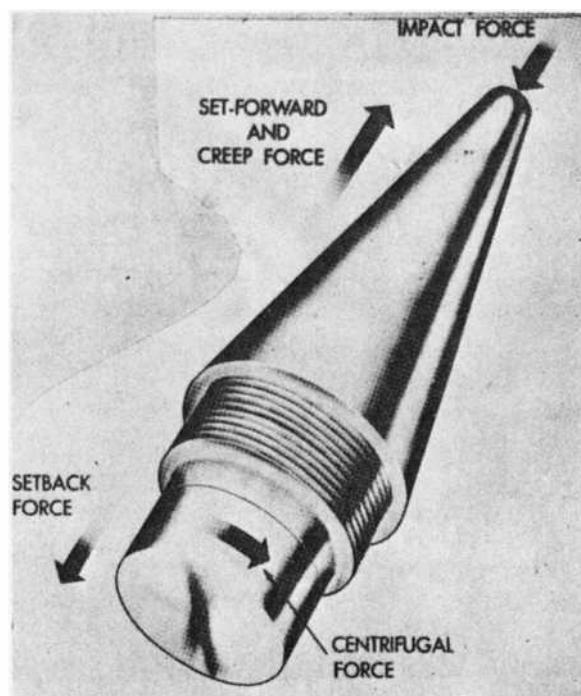
Fig. 12-1 *Principal forces used in artillery fuze design.*

(b) Setforward. The force of inertia or resistance to the extreme deceleration of the projectile upon impact with the target. This force is comparable to that which throws an automobile passenger forward when the brakes are applied suddenly.

(c) Creep. The force of inertia or resistance to the slow deceleration of a projectile during its flight from the instant the projectile stops accelerating until it reaches the target. This force produces a tendency for movable parts of the fuze to creep forward. It is actually a form of slow or weak setforward. Creep is also present in free falling bombs because components inside the bomb are capable of greater accelerations than the bomb body which is influenced by air resistance.

(d) Centrifugal. This force is caused by the rotation of spun projectiles. Whereas the force of setback exists only during the time the projectile is traveling down the bore, centrifugal force exists from the time the projectile starts to move until impact or detonation occurs. Centrifugal force is greatest where linear velocity is greatest ($F = Ma$; linear acceleration = r_ω^2 o $F = M_\omega^2 r$).

Whereas the above forces are the principal forces employed to actuate the various fuze mechanisms, other forces which are utilized include spring force, air or water pressure on the fuze, the force of friction, the pressure of the propellent gases in certain base fuzes for rockets, and the force of the air stream used to turn an arming vane for certain types of rocket and bomb fuzes. Electromotive force is becoming increasingly important in the design of fuzes for projectiles and missile warheads.

12-3.1 SAFETY FEATURES

Fuzes are designed to embody various safety features which will allow accurate control of their functioning. Prior to considering specific examples of mechanisms used to provide fuze safety, a discussion of the definitions associated with the field of fuze design will be undertaken.

(a) Definitions.

(1) Bore safety. A fuze is said to be bore safe when the explosive train is interrupted by a mechanical part between the detonator and the booster until the missile leaves the launcher. If the primer or detonator should accidentally go off while the missile is still in the launcher, the
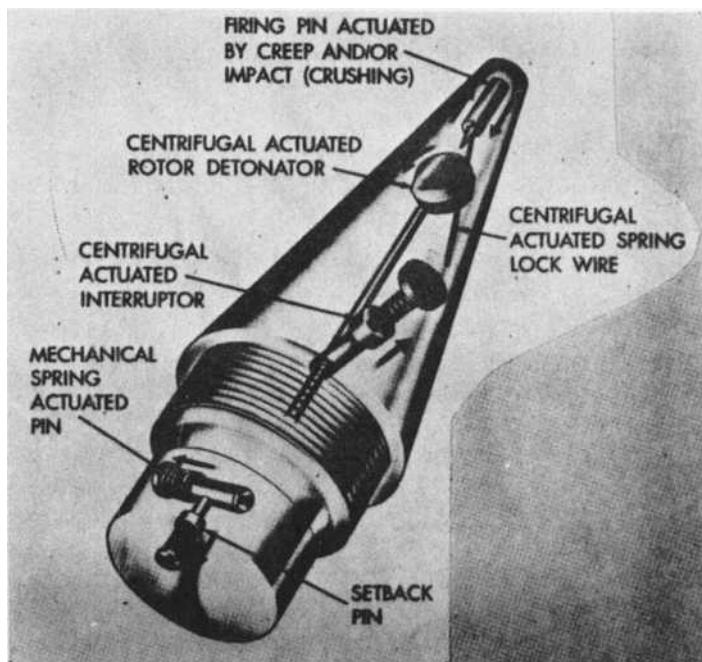
Fig. 12-2 *Examples of arming and safety devices.*

detonating wave could not reach the booster. The reason for not interrupting the explosive train between the booster and bursting charge is that the explosive force of the booster is so great that if it should go off prematurely in the launcher, it would blow through any safety device and set off the bursting charge.

(2) Armed. A fuze is said to be armed when a firing device is placed in condition to detonate on impact, influence, or at a preset time.

(3) Unarmed. An unarmed condition is obtained by a supporting device to hold the firing pin a short distance away from the primer; by a device which holds the firing pin out of direct line with the primer; or by a device which holds the primer or primer-detonator out of line with the firing pin and the rest of the explosive train. Fuze design must include a provision for arming the fuze before it reaches the target.

(b) Mechanisms. The required safety features of a fuze may be obtained by applying the available forces through various mechanical devices. Many of these devices are intricate.

(1) Centrifugal pins. Spring loaded centrifugal pins are mounted perpendicular, or nearly so, to the axis of the missile. The pin protrudes into, and prevents movement of other devices until centrifugal force moves the pin out of such device, compressing the spring which has been holding it in place.

(2) Setback pins. Spring loaded setback pins, similar to centrifugal pins, are mounted parallel to the axis of the missile so that setback force compresses the spring and pulls the pin out of the device into which it was protruding and restraining from movement.

(3) Centrifugal interrupter. The centrifugal interrupter is similar in operation to a centrifugal pin, but larger. It is used to block off the flash hole between the detonator and booster thus interrupting the explosive train. It is moved free of the flash hole by centrifugal force.

(4) Semple centrifugal plunger. The Semple centrifugal plunger is a typical example of an arming mechanism used in many of our base detonating fuzes (Figure 12-3). Although this plunger is operated primarily by centrifugal force, it also makes use of the force of setback to prevent arming until the missile has left the launcher, and of setforward force to actually drive the firing pin into the primer.

The firing pin g is mounted on its pivot j in a slot in the plunger body f. In the unarmed position of the firing pin, each safety pin h is pressed by its spring i into a hole in the firing pin and keeps the firing pin from rotating about its pivot j. A side blow which might compress one spring and permit the pin to leave the hole would force the opposite pin all the more firmly into its hole. For this reason it is practically impossible for the fuze to arm itself in transportation.

When the missile has attained a certain velocity of rotation the centrifugal force causes the safety pins to compress their springs and leave the hole h in the firing pin. The firing pin is then free to turn about its pivot j. The weight of the firing pin is so disposed with reference to its pivot that centrifugal force will tend to turn it about the fulcrum and arm it. However, the force of setback which acts on the fuze while the missile is still in the launcher overcomes the centrifugal force and holds the firing pin in the
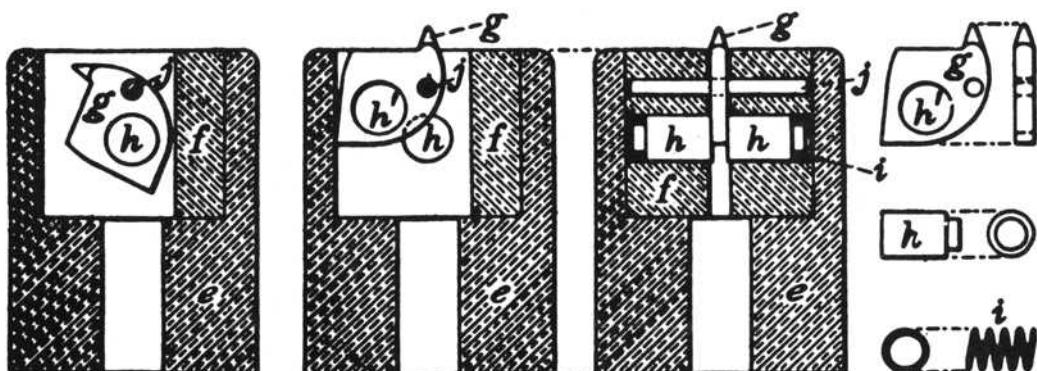
Fig. 12-3 Semple centrifugal plunger.

unarmed position until the missile has cleared the launcher. After cessation of the setback force, centrifugal force rotates the firing pin about its pivot and places it in the armed position. The forces acting tend to keep the firing pin in the armed position once it has been armed.

After the missile leaves the launching device, it is subject to retardation due to the resistance of the air. The plunger, f, not being subject to this resistance, tends to creep forward and bring the firing pin in contact with the primer. To prevent this, a restraining spring (creep spring), not shown in the Figure 12-3, is placed between the forward end of the plunger and the fuze housing.

(5) Rotor. The rotor (Figure 12-4) is an eccentrically weighted rotating body mounted so that its rotating axis is parallel to the axis of the missile. The rotor usually contains the detonator. Until the missile leaves the launching device, the rotor is held in such a position by centrifugal pins that the detonator is out of line of the flash hole and the explosive train, the flash hole being covered by a solid part of the rotor (Figure 12-4a). After the missile leaves the launching device, the centrifugal pins move out of the rotor, which then rotates about the rotor pivot pin until it comes to rest against the rotor stop pin (Figure 12-4b). In such a position the detonator is lined up with the flash hole leading to the booster. Operation of the rotor normally provides bore safety.

Some fuzes of late design incorporate a spherical rotor instead of the conventional flat rotor described in the preceding paragraph. Such rotors provide positive bore safety, prevent arming of the fuze for a short distance from the launching device, and thus greatly simplify fuze design by eliminating the necessity for a separate interrupter in the path of the impulse from the primer, or the additional flat rotor often employed in the booster. The delay is realized and may be varied in accordance with spherical rotor design, it being a function of weight distribution, i.e., the force exerted by the couple formed.

(6) Slider assembly. The slider assembly is a device somewhat similar to an interrupter; however, it is somewhat larger and also contains the primer or primer-detonator, which is held out of line with the firing pin and the rest of the explosive train until centrifugal force moves the slider over, bringing this first explosive component under the firing pin and in line with the other elements of the explosive train. In the case of a smooth bore mortar shell the slider is moved into the armed position by spring force.

(7) Devices which integrate acceleration (Figures 12-5 and 12-6). This type of device consists of several setback weights held forward by springs and so arranged that they must move back in sequence. The device is further arranged that if only some of the weights have moved back under the action of acceleration and the acceleration ceases, they all return forward so that the fuze cannot remain partially armed. The restoring springs also serve to increase safety because they set the threshold acceleration that is required before the elements respond at all.

In addition to these principal safety devices the following miscellaneous means are also used: Springs to overcome creep; crush collars to support the firing pin and hold it away from the primer until impact; shear wires and shear pins
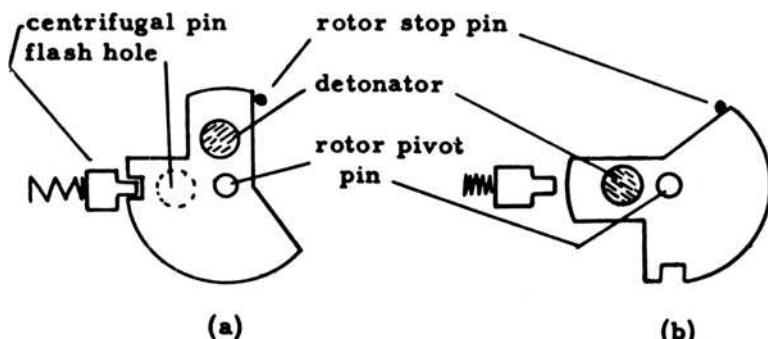
Fig. 12-4 Rotor.
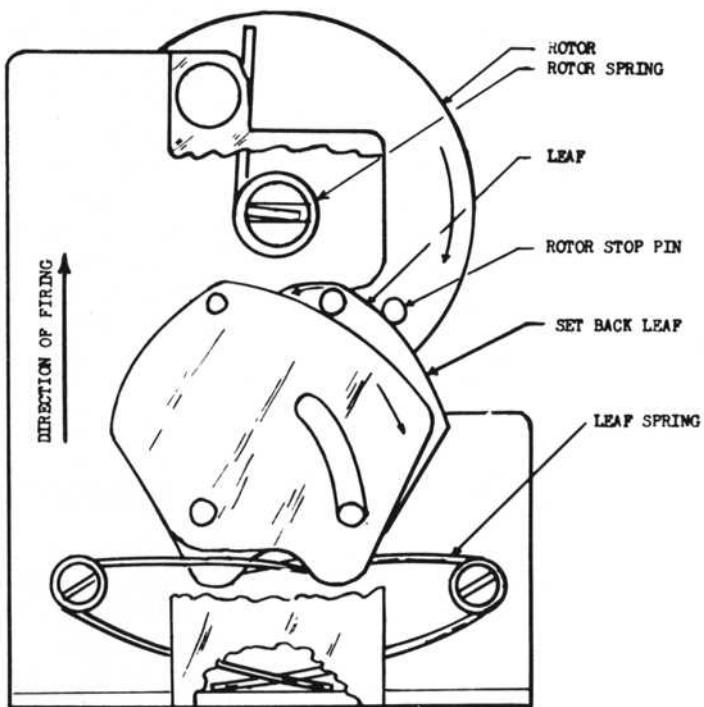
Fig. 12-5   Diagram of mechanical integrating accelerometer.
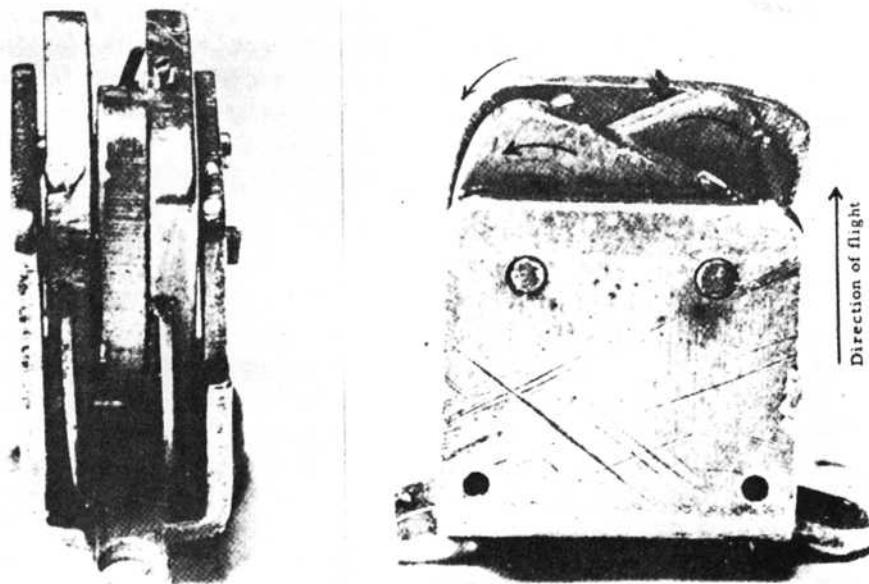
Fig. 12-6   Photograph of mechanical integrating accelerometer
(about four times actual size).

which restrain firing pins and plungers and which are sheared off on impact; resistance rings which hold a plunger in place by friction and which are overcome by setforward; half-rings and spiral wrappings which support the firing pin and which are moved out of place by centrifugal force after the projectile leaves the bore; cotter pins which restrain the movement of some mechanism and which must be withdrawn by hand before loading the projectile into the weapon (as is the case with the 60-mm and 81-mm mortar fuzes); shutters which contain the detonator holding it out of line with the firing pin until desired time of arming when spring action rotates the shutter to align detonator with firing pin and lead to booster.

In addition to these mechanical safety devices, many electrical devices are used in guided missile fuzes. Most missiles have electrical energy available for use in the guidance system; this energy can also be applied to the fuzing system. Safety devices in electrical fuzes will very often be of the type that interrupt an electrical circuit until activated. Among these are barometric switches, a bellows device which closes an electrical switch when ambient pressure reaches a predetermined value. Mechanical timing devices can also be used to close electrical circuits.

12-4 ILLUSTRATION OF DESIGN PRINCIPLES

In order to illustrate the application of some of these devices to fuze design, the functioning of an artillery fuze will be discussed in detail. Knowledge of the functioning sequence of this fuze is less important than an understanding of the operating principles.

This artillery fuze is a selective superquick or delay fuze. Either action can be obtained, prior to firing, by turning a setting screw in the side of the fuze.

The fuze (Figure 12-7) consists of a head A which carries the superquick element B; a body which carries the delay element L; setting device and threads assembling the fuze to the booster; a flash tube G which forms a channel for the superquick detonation and holds the head in its proper position; and an aluminum ogive F which continues the contour of the projectile ogive.

As issued by the Ordnance Corps, the fuze is set for superquick action. It is readily set and reset for either superquick or delay action by a setting sleeve I which for superquick action permits the interrupter J to move to its armed position, or which for delay action retains the interrupter in its unarmed position during the flight.

The setting sleeve is a cylindrical piece of brass with a slotted head and a central hole slightly larger than the diameter of the spring. The cylindrical piece contains a wide slot into which is fitted the spring and cup. Both the superquick and delay elements function on impact but, with a superquick setting, the faster action operates before the delay action, while with a delay setting, the superquick action is stopped at the interrupter. Where superquick action is desired, the setting sleeve is turned so that the screwdriver slot is in line with "S.Q." stamped on the ogive (slot parallel to longitudinal axis of fuze). When the slot is in this position, the setting sleeve is turned so that only the spring cup is in contact with the interrupter, thus permitting centrifugal force to move the interrupter and spring cup outward against the action of the interrupter spring. For delay action, the screwdriver slot in the setting sleeve is turned so as to be in line with the word "DELAY" stamped on the ogive (slot parallel to transverse axis of fuze). In this position, one of the legs at either side of the slotted portion of the setting sleeve overlaps the eccentrically located interrupter. The interrupter is thus retained in its unarmed or safe position during firing or flight.

Three major parts within the head comprise the superquick impact mechanism of the fuze. A cavity in the forward end contains a firing pin D, shaped like a large headed tack, and a gilding metal cup C which acts as a support for the firing pin. In a cavity below the point of the firing pin is the detonator assembly E. A washer holds the firing pin in place and a tinfoil closing disk seals the open end of the cavity to exclude foreign

A—Head

B— Superquick action

C—Gilding-metal cup

D—Firing pin for SQ action

E— Detonator

F— Ogive

G—Flash tube

H—Body

I— Setting sleeve

J— Interrupter

K— Interrupter spring

L— Delay plunger assembly

M—Firing pin for delay action

N—Primer

O—Black powder delay pellet

P— Delay-plunger pin lock

Q—Plunger pins

R— Detonating relay charge

S— Plunger support
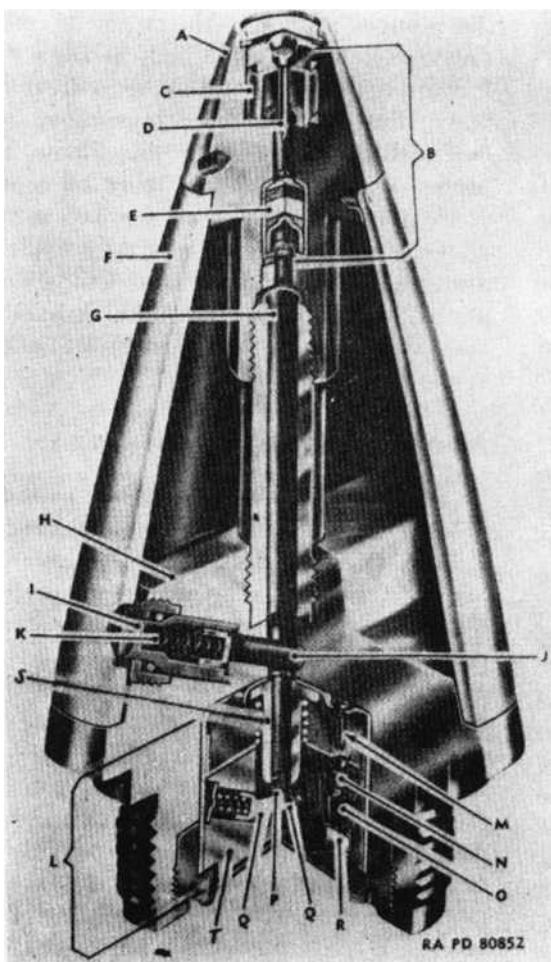
T— Plunger body

Fig. 12-7 M48A2 PD fuze.

matter.

The delay element *L* is contained in the rear of the fuze body. During transportation and firing, a plunger support *S* and centrifugal pins prevent the plunger body *T*, which carries the delay element, from contacting the plunger head which carries the delay firing pin *M*. The centrifugal pins *Q* and their springs are placed in the body, below the plunger support, in order to limit the possible movement of the plunger body until after the projectile has cleared the muzzle of the weapon. A plunger restraining spring coiled about the plunger support between the plunger head and the plunger body prevents these elements from contacting each other due to creep force during flight.

The delay explosive train consists of a percussion primer *N* which is actuated by the delay firing pin *M*, a delay pellet of compressed black powder *O*, and a relay pellet of lead azide *R* which transforms the combustion of the delay pellet into a detonation.

There are various safety features: The firing pin support *C* is so designed that it will not collapse under the force of setback (but will collapse under the force of impact) and supports the firing pin *D* at a safe distance from the detonator assembly *E*.

The interrupter *J*, while in its unarmed position closes the passage leading to the booster, preventing superquick action in the event the superquick detonator functions prematurely.

The centrifugal pins Q, in conjunction with the plunger support S, prevent the delay firing pin M from contacting the delay primer N until after the projectile has cleared the muzzle of the weapon.

The plunger restraining spring prevents the delay primer from contacting the delay firing pin as a result of creep force during flight.

When set for superquick action (Figure 12-8a), the interrupter is permitted to move outward as soon as it may overcome the friction due to acceleration (the component of the setback force perpendicular to the inclined axis) and the force of the restraining spring. This occurs after the projectile has emerged from the muzzle. Impact with earth or water ruptures the closing disk and forces the firing pin to the bottom of the cavity in the head. This action crushes the supporting cup and permits the point of the firing pin to penetrate the superquick detonator of lead azide priming mixture over lead azide. Impact with a resistant target such as concrete or stone will crush the head of the fuze with the same final effect. This action initiates a detonating wave which is free to pass directly through the open flash channel of the fuze to the detonator of the booster, the latter being in the armed position. It should be remembered that the delay firing pin also functions the delay element but, since the fuze is set for superquick action, the detonator of the booster functions prior to the completion of burning of the delay pellet.

When set for delay action (Figure 12-8b), the interrupter is restrained from outward movement in flight and, consequently, prevents the explosive wave of the superquick detonator from passing down the flash channel. On setback, the plunger support contacts the shoulders of the centrifugal pins, thus preventing the plunger head and delay firing pin from contacting the plunger body and delay primer. Centrifugal force moves the two centrifugal pins to their outermost position, compressing the springs behind them as soon as linear acceleration has been overcome. The delay element is fully armed about 3 to 5 feet beyond the muzzle of the weapon. During flight, the plunger body and delay primer are prevented from contacting the plunger head and delay firing pin by means of the plunger restraining spring which surrounds

the plunger support. On impact or retardation (ricochet), the plunger body is forced by setforward to move forward in the cavity of the fuze body, thus carrying the delay primer into contact with the delay firing pin. Flame from the primer ignites the delay pellet of compressed black powder which burns for 0.05 second and ignites a relay pellet of lead azide which transforms the combustion into a detonation which passes through an auxiliary flash channel into the main flash channel, and thence to the detonator of the booster.

12-4.1 BOOSTER, M21A4

(See Figure 12-9.) The combination of the M48 series fuze with the M21A4 booster provides a bore safe assembly since the rotor of the booster restrains its detonator out of line with the flash hole connecting the detonator of the fuzes with the closing cup charge of the booster, and positively interrupts the channel until the projectile has cleared the muzzle of the weapon. The functioning of the M21A4 is quite interesting. On setback, the centrifugal pin lock pin moves rearward against the pressure of its spring, and it is then locked in its rearward position by centrifugal force which causes the end of the pin to engage the projection on the centrifugal pin screw. When centrifugal force is great enough to overcome the frictional forces resulting from acceleration, the centrifugal pin is thrown outward releasing the rotor which contains a detonator of lead azide over tetryl. The rotor, upon being released, moves by centrifugal force about its pivot until it strikes the rotor stop pin, this being the armed position. This action is completed when the projectile has cleared the muzzle by from 3 to 5 feet. In the armed position, the booster detonator (in the rotor) is in the center of the booster and thus in line with the flash channel of the fuze. To insure that the rotor will remain armed, it is locked in the armed position during the remainder of its flight by the rotor lock pin which is thrown outward by centrifugal force into the hole closed by the body plug. During flight the rotor lock pin lock moves by creep force behind the rotor lock pin and thereby restrains the latter from possibly moving inward. Both these locking devices are contained within the rotor, the lock pin in a recess
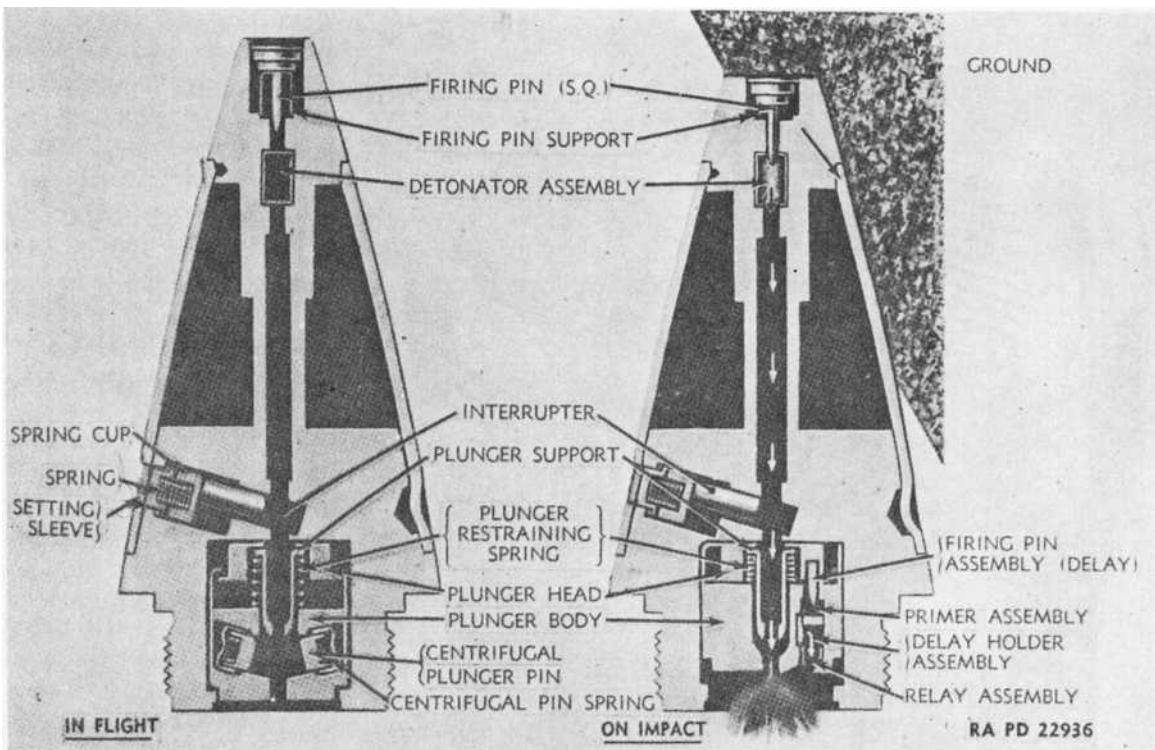
Fig. 12-8a   M48A2 PD fuze set for superquick.
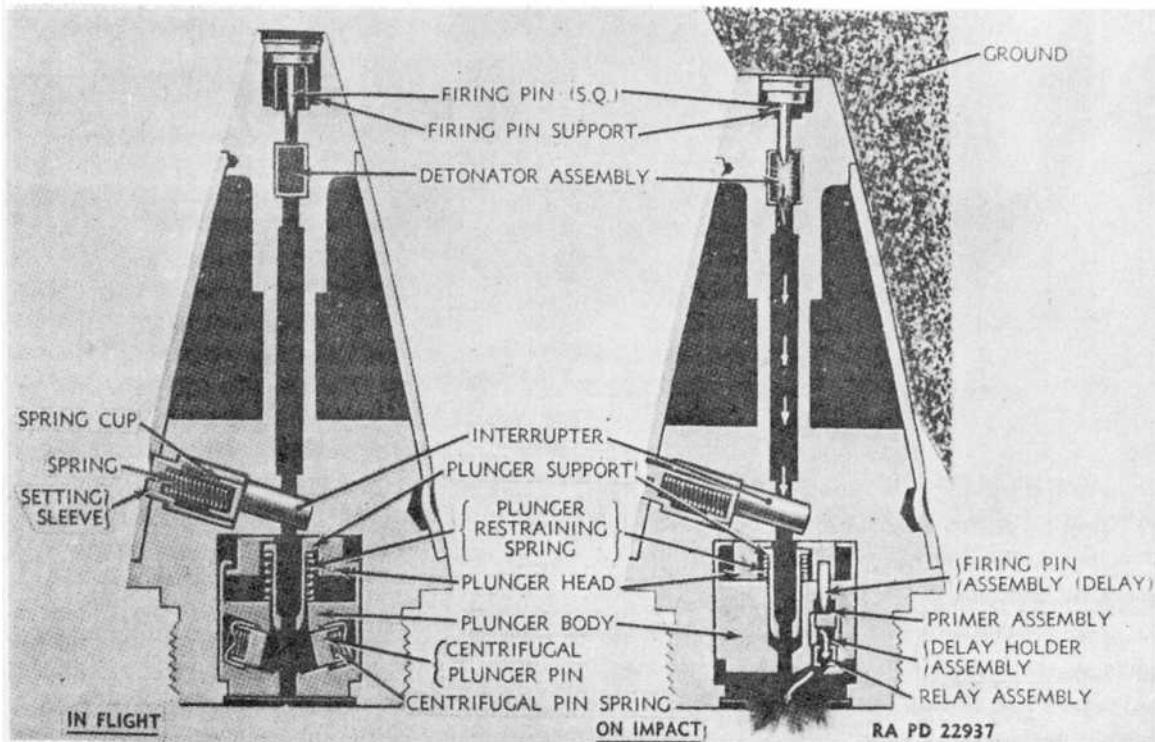
Fig. 12-8b   M48A2 PD fuze set for delay.

A—Brass body

D—Brass cover

E—Onion-skin paper disk

F—Rotor stop pin

G—Detonator (lead azide-tetryl)

H—Rotor

I—Rotor lock pin

J—Rotor lock pin lock

K—Centrifugal pin

L—Rotor pivot pin

M—Booster lead (tetryl)

N—Booster cup

O—Booster charge (tetryl)

P—Centrifugal pin lock pin
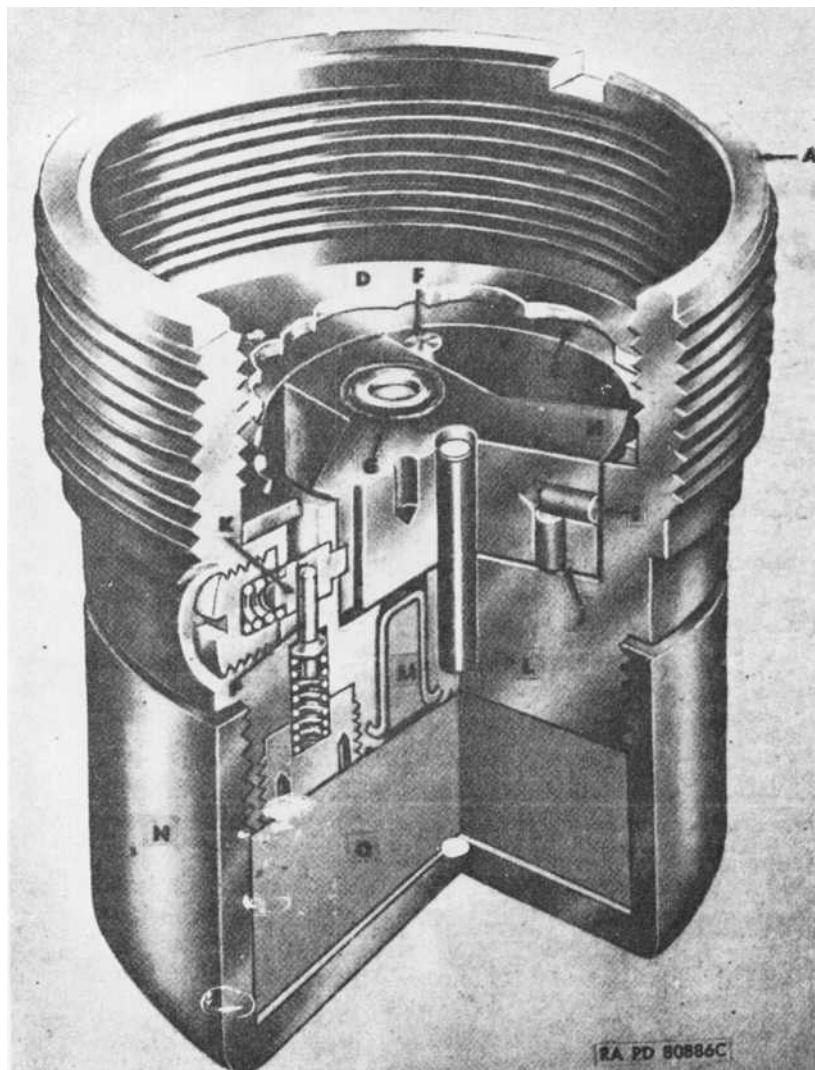
Fig. 12-9 M21A4 booster.

drilled into the side of the rotor, and the lock pin lock in a recess which communicates with the recess for the lock pin drilled into the bottom of the rotor. Action of the fuze will now successively explode the rotor detonator of lead azide and tetryl, the closing cup charge of tetryl, and the booster pellet of tetryl.

The functioning of this fuze is typical of the fuzes used with artillery, mortar, bomb, and small rocket fuzes. These types differ in that the various forces and effects are differently utilized depending upon the particular mission performed and the type of weapon from which the fuze is fired. For example, centrifugal force cannot be utilized in rounds which are not spin stabilized. For functioning of other specific fuzes, it is recommended that the reader consult TM9-1901, *Artillery Ammunition*.

12-5 THE RADIO PROXIMITY FUZE

For certain targets, such as exposed personnel and aircraft in flight, it is desirable to have a projectile burst near, but before actual contact with the target. Such a burst will permit better dispersal of fragments, thus giving a great increase in the effective area of the burst. The desirability of air bursts led to the early development of time fuzes, which were designed to function after a preset time and, it was hoped, explode the missile in the immediate vicinity of the target. Time fuzes (whether mechanical or powder train) could not be made which would perform regularly with the split second accuracy required to knock a plane from the sky, or to cause bursts at the exact height above an enemy infantry position which would inflict the maximum number of casualties. For many years, the artilleryman's dream was to have a fuze available that would, at an optimum distance from the target, give the most effective burst possible for the particular round. Fuzes of this type, which function as they approach the target, are called proximity fuzes, and military scientists have long been working on their development.

The great problem of how to get the fuze to sense the target has been attacked in many ways. Among the principles upon which experiments have been based are radar, radio, acoustic proximity, electromagnetic proximity, electrostatic proximity, and photoelectric cells.

Research is still being conducted to perfect fuzes using all of these proximity agents, but the only successful proximity fuze produced to date is the radio proximity fuze. This fuze first became available to U.S. and Allied Forces during World War II.

The radio proximity fuzes so far developed are all generally similar in that they have corresponding elements. The differences involve such factors as size, shape, detailed circuitry, and the types of safety devices and electric power supply employed. The basic components are (Figure 12-10):

(a) A radio transmitter and receiver composed of subminiature vacuum tubes, which in the case of artillery fuzes must be rugged enough to withstand accelerations of 20,000 g's when fired. It is believed that transistors and printed circuits will be very useful in newer fuzes for this category of component.

(b) A selective amplifier.

(c) An electronic switch.

(d) A miniature battery or generator to provide electrical power.

(e) Safety devices to prevent operation of the fuze during storage and handling, and until it has traveled a safe distance after firing.
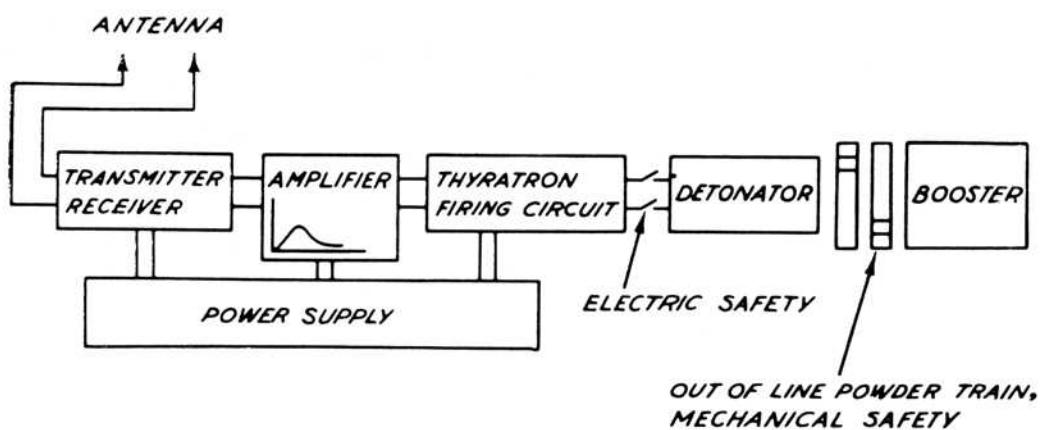
Fig. 12-10 Block diagram of typical VT fuze system.

12-5.1 FUNCTIONING OF A TYPICAL ROCKET OR BOMB VT FUZE

The radio proximity fuze is a fine example of the application of basic principles (in this instance electronics and radio) to the solution of a problem generated in the field of terminal ballistics. To illustrate this, the operation of a typical proximity fuze will be discussed.

The projectile itself serves as the transmitting and receiving antenna. The fuze circuit is indicated schematically by the block diagram which shows functionally the various assemblies that comprise a fuze (see Figure 12-10).

When the projectile is fired the power supply is activated.

In general, two types of power supplies are employed.

(a) Artillery projectiles use a wet cell electrolytic battery for power. The electrolyte is contained in a glass ampoule which is shattered on setback. Centrifugal force causes the electrolyte to be distributed among the plates of the battery so that the battery becomes activated.

(b) In bombs and some nonrotating projectiles, wind driven generators are used to supply power (Figure 12-11).

Within a fraction of a second after launch the fuze circuit warms up and all transients die out so that the fuze is ready for operation by the time the safe distance has been traversed and arming is completed.

The remainder of the operation can best be understood by first considering in more detail what goes on outside the fuze, and then the resulting sequence of internal operations.

12-5.2 EXTERNAL PHENOMENA

To consider what goes on outside, suppose that the fuze has come close enough to its target to receive appreciable reflection. The current in the antenna sends out a continuous wave; part is reflected back and sets up a small voltage in the antenna which is proportional to the antenna current but not necessarily in phase with it. Thus the presence of the reflecting target has the effect of changing the antenna impedance by an amount Z such that

$$Z = \frac{e}{I}$$

where I is the antenna current and e is the voltage due to the reflected radiation. As the distance to the target decreases, two things happen: (1) The size of e increases as the reflection gets stronger; and (2) The phase between e and I changes by 180° each time the distance is reduced by a quarter wave length.

A simple vector picture shows what goes on as the fuze approaches the target.

In Figure 12-12, Z_o represents the antenna input impedance (usually resistive as the antenna is tuned to resonance) when there are no reflectors near by. Z represents the impedance due to the reflector. As the fuze approaches the target the end of Z traces out a spiral shown by the dotted curve. The total antenna impedance Z_T thus varies periodically from minimum (point A) to maximum (point B) going through one cycle each time the path shortens by $\lambda/2$. If the velocity of the fuze toward the target along the line joining them is v, then

$$f = \frac{v}{\lambda/2} = \frac{2v}{\lambda}$$

where f is the rotational frequency of Z, and λ is the wave length of the transmitted signal. This has been called the Doppler frequency since the same answer is obtained if difference between transmitted frequency and received frequency is calculated taking account of motion of fuze and target.

Figure 12-13 represents the situation when a projectile passes a target. The dotted curve plotted along the trajectory represents the resistance component of Z_T at each point as the projectile moves along. This is an idealized curve simplified for clarity. The actual wave is much more complicated.

It can be shown that

$$v = V_0 \sin\theta$$

$$f = \frac{2V_0 \sin\theta}{\lambda}$$

where v is the velocity of closing between projectile and target and V_0 is the speed of the projectile in a coordinate system attached to the target. Thus, as the fuze approaches the target the size of Z grows rapidly because the distance

VANE LOCKING PIN HOLES

METAL VANES

VOLUME OCCUPIED BY ELECTRIC GEAR

GENERATOR

WORM GEARS

GEAR TRAIN

ARMING SHAFT

FIRING CONDENSER

FIRING CIRCUIT CONTACTS

ELECTRIC DETONATOR

SAFETY PIN SLOT

DETONATOR ROTOR

BOOSTER LEAD-IN

BOOSTER SAFETY PIN

RAPD 58763

METAL RING

VANE LOCKING PIN

PLASTIC CONE

PLASTIC DRIVE SHAFT

ARMING SHAFT GEAR SECTOR

SETBACK WEIGHT

WRENCH LUG

ARMING SHAFT TENSION SPRING

ROTOR HOUSING

ROTOR DETENT

BOOSTER LEAD-IN PLATE

BOOSTER

BOOSTER RETAINING SLEEVE

Fig. 12-11   Ring-type VT fuze, for bombs or rockets.

shortens and the directivity improves. Also the rotation of Z slows down from the value:

$$f = \frac{2V_0}{\lambda}$$

at large distances to the value

$$f = 0$$

at the instant when $\theta = \upsilon$.

To sum up, the characteristics of Z are: rapidly growing amplitude and rapidly falling frequency as the fuze approaches, and the reverse as it passes beyond the target.

12-5.3 INTERNAL ACTION

With the above information the internal action of the fuze can now be examined in some detail:

12-5.4 RADIO FREQUENCY SECTION

When the effect of the reflecting target is expressed as a change of antenna impedance in the manner outlined above, it is easy to see how a single tube can perform the three following functions.

Transmit CW
Receive the reflected signal
Separate the low frequency component

All that the transmitting tube sees is a variable load which changes periodically from increased resistance, to increased reactance, to decreased reactance, to decreased resistance. Assume that the oscillator is tightly coupled to the antenna via its plate circuit: The small reactance changes will alter the frequency of oscillation slightly with but little effect on oscillator performance,
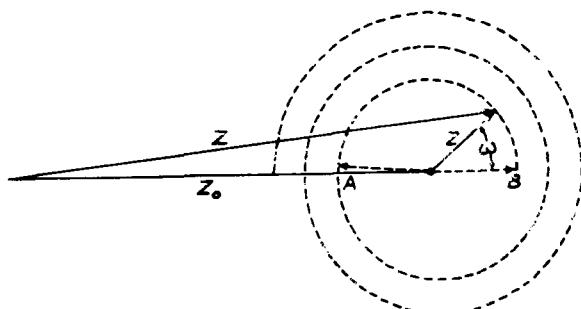
Fig. 12-12 Change of antenna impedance as fuze approaches the target.
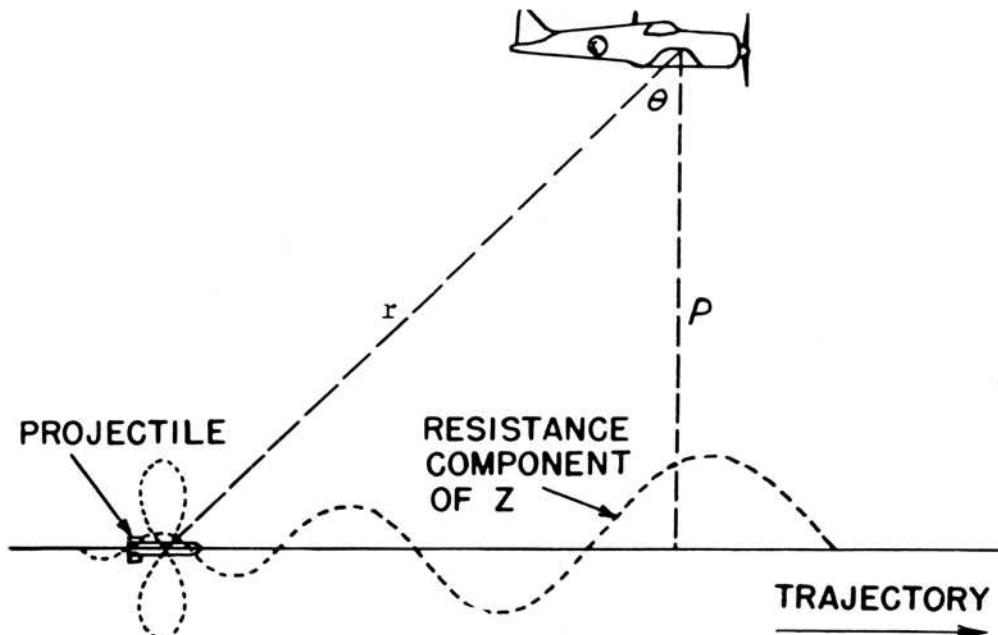
Fig. 12-13 Variations of Z in neighborhood of a target.

and the detected output voltage will have in it an alternating component

$$f = \frac{2v}{\lambda}$$

This can be separated and used as a working signal.

The RF circuit problem boils down to a problem of designing an oscillator which can work effectively into a very wide range of radiation resistances and respond to very small changes in them. Such an oscillator was found to be plausible and is employed in VT fuzes.

12-5.5 AMPLIFIER CIRCUIT

Since the signal from the radio frequency sections is too small to actuate a firing device directly, it is necessary to amplify it. The primary function of the amplifier is to magnify this signal until it can reliably operate a thyratron firing tube. The amplifier performs important secondary functions however: By shaping its gain characteristic properly it assists the directivity pattern in properly locating the point of burst; it suppresses much of the tube microphonic noise; and by proper design it suppresses hum from AC operation of the tube filaments.

The frequency of maximum gain is selected by trial to give proper burst location. As the fuze approaches the target, the frequency first received is too high and the gain is small. When it gets closer the output of the amplifier grows because (a) the distance is less and input signal is greater; (b) because the target is in a better position to be seen and the input signal is greater; and (c) because the frequency is lower and the gain higher. All three factors combine to give a very steeply rising amplifier output. In effect, the contribution of all factors makes the region of influence around the fuze much more sharply defined than the directivity envelope alone would indicate.

12-5.6 FIRING CIRCUIT

The fuze functions and bursts the projectile when the output from the amplifier increases beyond a certain critical value. The vacuum tube in the firing circuit is a small thyratron developed for the purpose. It will be remembered that a thyratron is a gas filled triode. When the grid of a thyratron is biased below cutoff, the tube will

not conduct. If a positive potential of sufficient magnitude is applied to the grid, the gas in the tube ionizes and conduction begins. Unlike a vacuum triode, however, plate current is not proportional to further increases in grid voltage. Instead, when conduction begins, a heavy plate current will flow and the thyratron tube becomes a virtual short circuit. The thyratron in the VT fuze is biased to the proper level so that the burst will be properly located. This bias is determined by experimentation.

The actual detonation is started by discharging a small condenser through the thyratron to an electric detonator similar to a blasting cap. The cap sets off the powder train which in turn sets off the booster which detonates the main charge. The time from firing pulse on the thyratron until the fragments start leaving the projectile is about one millisecond, during which time the projectile moves very little.

Small though it is the thyratron passes very large peak current and can do so many times before its characteristics begin to change. This allows proper testing in the fuze factory. The power supply is not capable of passing current enough to fire the electric detonator. It is the high instantaneous surge from the final filter condenser that supplies the energy.

12-5.7 ELECTRICAL SAFETY DEVICES

All VT fuzes have several electrical safety devices which prevent their premature operation upon firing or if handled roughly. Some of these, which vary with the type of fuze, are listed below:

(a) Battery activation for artillery fuzes. This element of safety is provided by the time and means required to activate the battery as discussed in Par. 12-15.1.

(b) Resistor-condenser time. The current developed by the battery or generator flows through the firing circuit where another safety feature is provided by a resistor and condenser combination. The passage of current is restricted by a fixed resistance in its flow into a condenser of known capacity. The time required for the condenser to reach its firing potential provides a means of determining arbitrarily the minimum arming time of the fuze. This time is approximately 0.3 second for standard antiaircraft artillery and approximately 1.0 second for field

C—Plastic ogive

D—Radio assembly

E— Shield can

F— Fuze base

G—Battery plates

H—Electrolyte ampoule

I— Ampoule support

J— Self destruction switch

L— Electric squib

M—Auxiliary detonator assembly

N—Booster

O—Rear fitting
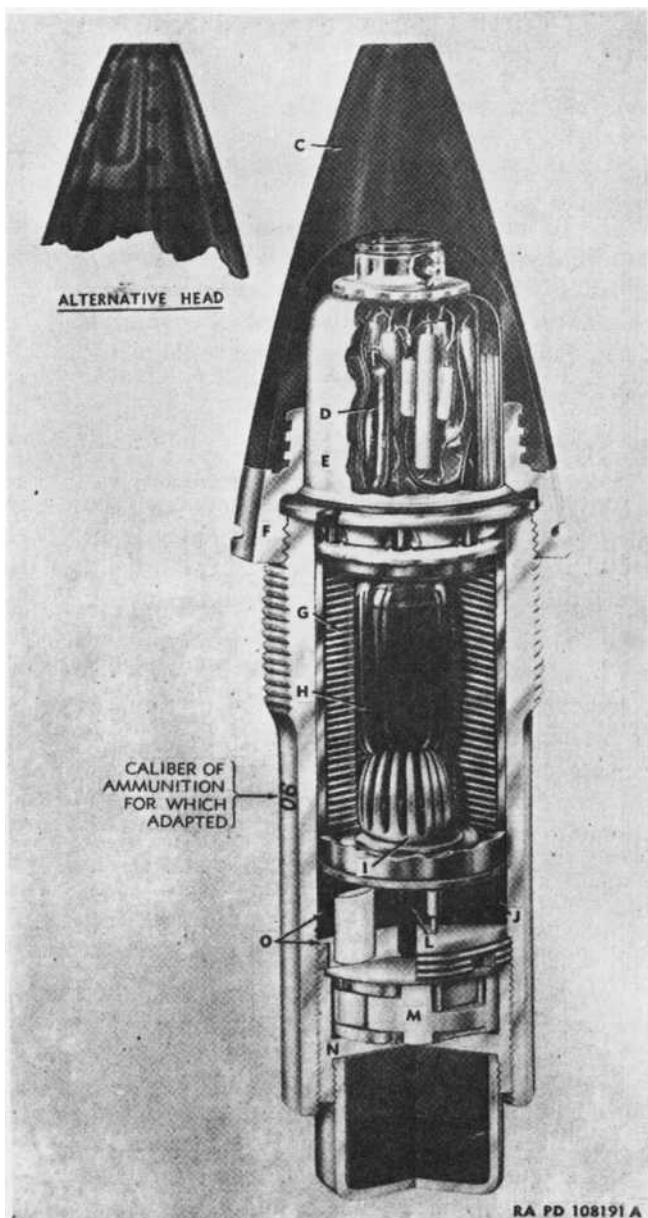
Fig. 12-14   Artillery VT fuze.

artillery fuzes.

(c) Self-destruction switch, (for antiaircraft). This is a closed switch placed in the circuit to short circuit the thyratron tube which acts as a firing switch; it also serves to drain the condenser of any voltage set up during handling and shipping. Centrifugal force causes the switch to open and remain open as long as rotational velocity is high enough. When rotational velocity drops to a certain predetermined level, the switch closes again, short circuiting the thyratron tube and exploding the round.

(d) Rear fitting (arming mechanism). Part of the arming mechanism short circuits the electric primer (squib) and also removes it from the rest of the firing circuit. This short provides
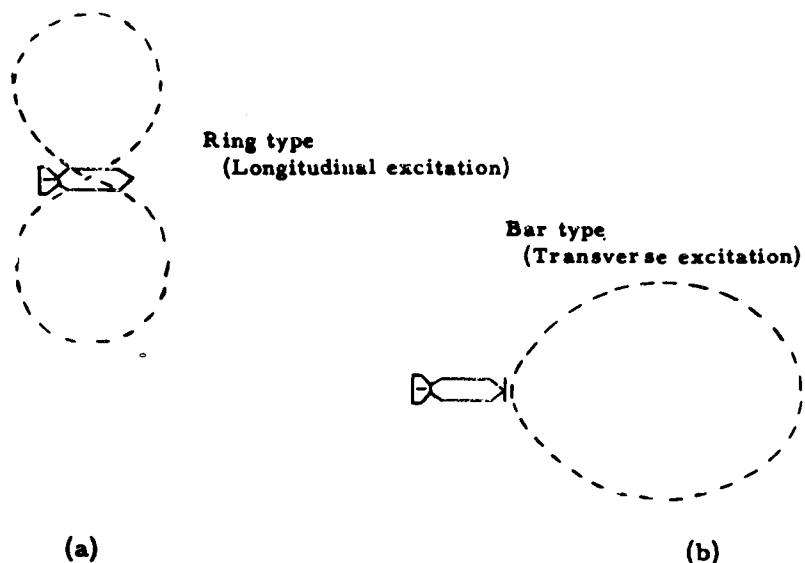
Fig. 12-15 Directional sensitivity patterns.

a path for the flow of current around the primer during handling and for about a second after the round has been fired from the weapon. It is also constructed so that centrifugal force is necessary to cause the rear fitting to operate.

In addition to special electrical safety devices, VT fuzes include mechanical safety features comparable to those found in regular artillery fuzes. Interrupters are safety devices located in the auxiliary detonator. Each consists of two rotors or plates which, when unarmed, are locked in position over the detonator, one covering each end of the detonator. These provide detonator safety in the fuze.

An impact element is used in antiaircraft and ground artillery VT fuzes. It is designed to function the round on impact when the radio section fails to operate normally.

12-5.8 GENERAL CHARACTERISTICS

A projectile or bomb must burst at a certain distance from the target for the ensuing blast and fragments to be of maximum effect. The burst distance will vary slightly since it is a function of the angle of approach to the target, which in turn depends on the shape and location of the field of sensitivity of the VT fuze. With this phenomenon in mind, the burst distance may be varied by varying the antenna type used (Figure 12-15) and/or the angle of approach of the missile for the same target.

Figure 12-15 shows antenna directivity patterns for two common types of antennas. These directivity patterns are actually figures of revolution about the axis of the projectile. In actual practice, there is an effective directivity pattern for a VT fuze somewhat different from that shown. It will be recalled that the detected Doppler frequency is amplified to provide the firing signal. As the velocity of closing between missile and target changes, the Doppler frequency changes. The amplifier can be made to have a very high gain at a particular frequency; for other frequencies its gain will be lower. Thus, the point of burst can be more closely controlled than would be indicated by the directivity envelope above. If a series of targets moves past the fuze at different distances and points of burst are plotted, the shaded area of Figure 12-16 would actually describe the region of influence.

For ground artillery fire, it can be seen from Figure 12-15a that burst height is controlled to a certain extent by angle of fall of the projectile. For the type of antenna illustrated in Figure 12-15a, a steeper angle of fall will give a lower height of burst.

The burst height may also be influenced by characteristics of the target itself, such as the degree of moisture contained in the target area, ranging from low burst height for dry soil targets to maximum burst height over a watery
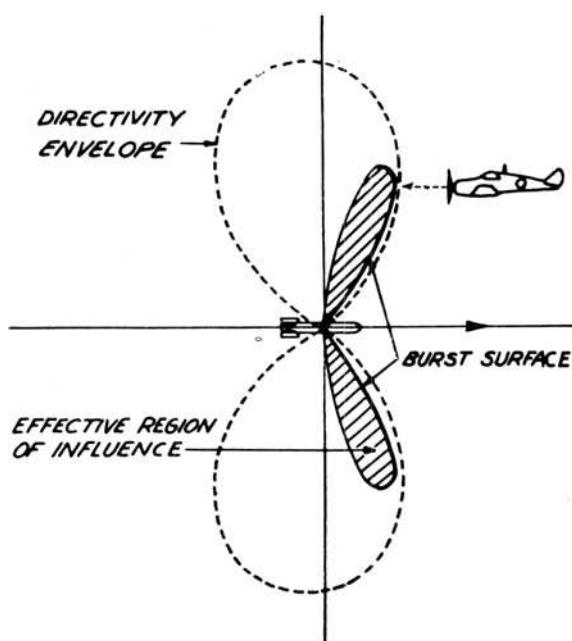
Fig. 12-16 Relation between directivity envelope and burst surface.

target. If the target area is wooded, especially with deciduous trees (trees which have broad leaves), the burst height may be increased as much as the height of the trees themselves, depending on the density of the woods. Some target materials, such as tow target sleeves, may reflect waves of such low amplitude that the fuze fails to function the round on the target.

VT fuzes are useful wherever air bursts are desired, but cannot be used against many types of targets. They are extremely effective against personnel in uncovered positions, since bursts occurring overhead will reach even into foxholes.

They are also extremely useful against light materiel such as aircraft or trucks. However, they are not effective against armored vehicles or against any target where penetration before bursting is desired.

Early model VT fuzes were armed as soon as the electrical safety delays had completed their operation. This resulted in many early bursts from low, dense cloud formations, hill masses over which the projectile passed within burst height, or other objects within bursting radius. This condition was dangerous in many cases and led to the development of controlled arming (CVT) proximity fuzes. All VT fuzes being produced today are of the CVT type. There are in general, two types of CVT fuzes:

(a) The bracket arming type fuze is for use against airborne targets. At (predicted time-to-target) settings greater than 3 seconds, the VT element of the fuze becomes armed at approximately 2 seconds prior to the set time and will then detonate the shell upon proximity approach (within approximately 60 feet) of a suitable airborne target. If no suitable target is encountered, the fuze will detonate the shell at approximately 2 seconds after the set time. The impact element will cause the fuze to function with superquick action.

(b) The adjustable delay arming type fuze is for use against terrestrial targets. These fuzes are totally inoperative (for safety reasons) for 2 seconds after firing. The VT fuze element becomes armed approximately 3 seconds prior to the set time and will function on proximity approach to any land or water mass. The impact element becomes armed 2 seconds after firing, regardless of setting and remains armed until the fuze detonates.

12-6 FUZES FOR GUIDED MISSILES

The fuzing requirement for guided missiles is basically the same as for smaller projectiles. The missile must be safe to handle and the fuze must initiate detonation with a high degree of reliability. In fact, reliability for guided missile fuzes must be even greater than for artillery or high explosive bomb fuzes, since the cost of

these missiles is great and they may carry nuclear warheads. At the same time, the probability of a premature burst must be cut to a very low figure since the premature explosion of a nuclear warhead would be far more disastrous than would the premature explosion of a high explosive warhead. The probability of premature

arming can be reduced by using three similar arming devices and requiring that all be armed before fuze functioning is possible. This, however, will also reduce the reliability of arming at the proper time. In effect, each individual arming device must be manufactured so that its arming reliability is very high in order to obtain sufficient overall arming probability. Alternatively, an additional arming element (consisting of three devices) of the same type can be utilized such that arming will be accomplished if either system arms. In this way probability of proper functioning can be increased while probability of improper functioning is decreased. This redundancy of fuzing is possible in large missiles because space restrictions are not nearly so acute as in smaller projectiles. The actual fuzing system may differ considerably in detail from smaller, self-contained fuzes; however, the same basic forces are utilized and the same basic principles apply in obtaining fuze operation. Many missile fuzes employ a radio proximity fuze for the detonation signal. However, to control burst height more closely; to avoid counter-measures; and to assure that the missile is over the proper target, more complex circuitry is required.

In some missiles employing a command guidance system, the fuze is closely integrated with the guidance, and the actual fire signal is transmitted from the ground station when the proper intercept point is reached. In this case, the safety and arming devices will be in the missile, but the safety and arming signals may come from the ground control as does the fire signal.

In general, there is no standard missile fuze as is the case with some general purpose artillery fuzes. Instead, the fuze becomes part of the weapon system and is designed especially to suit the needs of that system.

REFERENCES

1 Merrill, Goldberg, Helmholz, *Principles of Guided Missile Design—Operations Research, Armament, Launching,* Princeton, N.J., D. Van Nostrand Co., Inc., 1956, pp 287-330.

2 Page and Astin, Survey of Proximity Fuze Development, *American Journal of Physics,* Vol. 15, No. 2, pp 95-110, March-April, 1947.

3 Department of the Army Technical Manual, TM9-1901, Washington, U.S. Government Printing Office, 1950, pp 242-353, 369-380.

APPENDIX A

GUN TUBE CONSTRUCTION

A-1 SELECTION OF METHOD

The primary objectives of gun design and construction are as follows:
(a) Increase muzzle velocity
(b) Increase rate of fire
(c) Increase life of barrel
(d) Reduce weight, especially for airborne uses
(e) Make guns big and flexible, yet use existing transporters

In achieving such objectives, the selection of the method of gun construction must involve the detailed cognizance and appreciation of the following factors:

(a) Availability of facilities
(b) Economy in raw materials
(c) Rate of production
(d) Adaptability to mass production
(e) Availability of labor
(f) Cost

A-2 SHAPING THE TUBE

From early days through the Civil War practically all cannon were made by the time honored method of casting. At first iron was used, then brass and bronze, and finally steel. Strength was increased by simply adding more metal to obtain greater wall thickness. Then in the latter part of the 19th century the process of hot-working large pieces came into use and guns, single-tube and built-up, were made by forging. The demand for stronger yet lighter guns provided initial impetus to the development of fine steels, not only as to composition of the metal but also as to its heat treatment. Specifications were high and the processing was relatively slow so that production was limited; costs too were high as was usage of critical materials.

This situation was clearly realized during the period between World War I and World War II, and much experimentation was done to devise new methods of gun construction. Out of this developmental work came the new production methods for making monobloc tubes by centrifugal casting, and processes similar to those used in producing seamless steel tubing. In any volume production program small and medium caliber guns will be produced by one or both of these processes in addition to those produced by forging. The comparatively few large caliber guns will probably still be made by forging.

Centrifugal casting of tubes can be used in volume production for cannon up to and including the 90-mm gun and the 105-mm howitzer. This process (Figure A-1) involves pouring molten metal (alloy steel) into a cast iron chill mold as it is rotated in a horizontal position at speeds from 900 to 1750 rpm. The centrifugal force causes the metal to take the shape of the mold (a conical section) as it solidifies; impurities move toward the center and can be bored out.

After about 10 to 25 minutes, when the casting has cooled sufficiently to handle, the red hot casting is pushed out of the mold and buried in cinders to cool for up to 48 hours. Normalizing, quenching, tempering, turning and boring of the tube, and cold working (autofrettage) follow in that order. Since the centrifugal casting of long heavy wall sections, such as are required in gun tubes, has not found a commercial application, the government has maintained stand-by plants for the manufacture of these important items. This insures volume production of medium caliber cannon early in an emergency.

The other recently perfected method consists of producing gun tubes from seamless steel tubing. This process involves heating a steel bar of
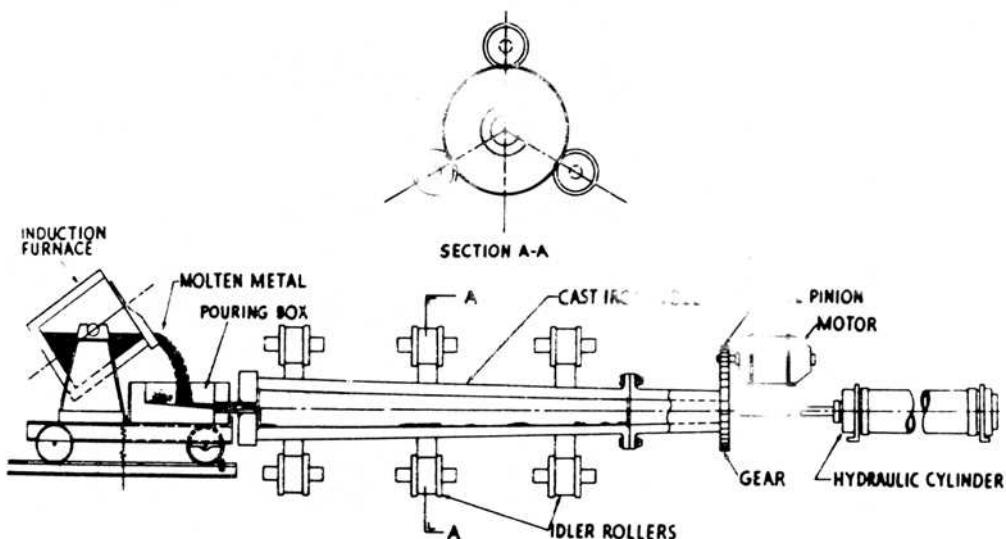
Fig. A-1 Centrifugal casting.

gun tube size, piercing it, and upsetting the breech end (if a heavy breech section is required). Piercing hot works the metal as in forging. Proof tests of such tubes are comparable to guns made by conventional methods. Many 40-mm and 75-mm tubes were produced from seamless tubing during the war. With this method large quantities of gun tubes could be produced without the necessity for extra bloom heating and forging capacity; existing rolling and piercing mills can be utilized entirely in this process. Piercing (Figure A-2) takes 15 seconds contrasted to 6 hours for the former forging and drilling operation. The upsetting of the breech takes 5 seconds and eliminates the need for machining, casting, or forging the breech from a bar of breech diameter, and more than 5 hours production time can be saved in boring the tube. The saving of scrap or waste metal is also readily apparent.

A-3 ASSEMBLY AND STRENGTHENING OF COMPLETE TUBE

The advantages, in weight saving and higher permissible powder pressures, of having the inner fibers of a gun tube under an initial tangential compressive stress, have already been discussed. An early method of achieving this was to wrap wire under tension around the gun tube. This method is now obsolete for large guns, since inadequate longitudinal strength caused drooping of the tube and greater whip action under the firing stresses. Rocket launchers were wire wrapped around the portion where maximum pressure occurred.

The next method used was to build up a gun by shrinking one or more cylinders, called jackets or hoops, around a gun tube. Guns from 6 to 18 inches in caliber were made in this manner. The 280-mm gun tube now being produced is built up. The inside of the jacket is made slightly smaller than the outside diameter of the tube. The jacket is expanded by heat until it fits over the tube. Then, as it is cooled, the jacket shrinks into place, putting the tube into a state of compression and in effect increasing the strength of the gun. It may be seen that the tolerances between jacket and tube necessitate highly accurate machining of both contacting surfaces. Jackets were formerly heated by electrical elements and required approximately 17 hours to reach the necessary temperature (Figure A-3). Recent
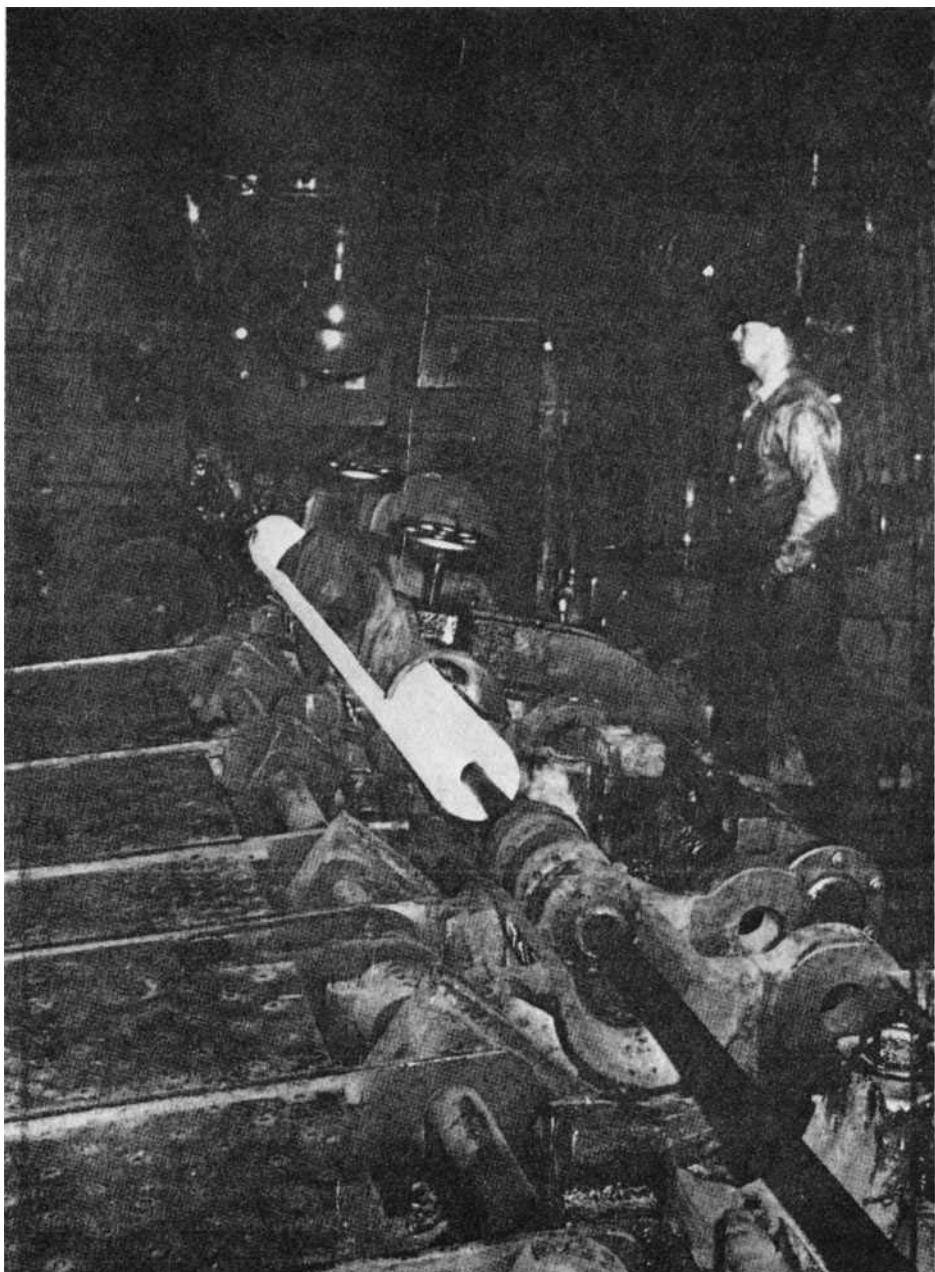
Fig. A-2 Piercing operation in making heavy gun tubes from seamless tubing (courtesy Timken Roller Bearing Company).

studies indicate that this heating can be accomplished by induction heating in about one hour.

With guns of smaller caliber where lower powder pressures are permissible, monobloc or one piece construction is used, including various heat treating and cold-working processes. Guns of up to 8-inch caliber may be made in this manner, starting with the tube forged, centrifugally cast, or made from seamless tubing.

With such a monobloc construction the cold working or self hooping process may be employed, in which the interior portion of the tube is hydraulically stressed, without being heated, beyond its elastic limit. The outer fibers of the tube then act like a hoop or jacket in tangentially compressing the inner portion. This process was
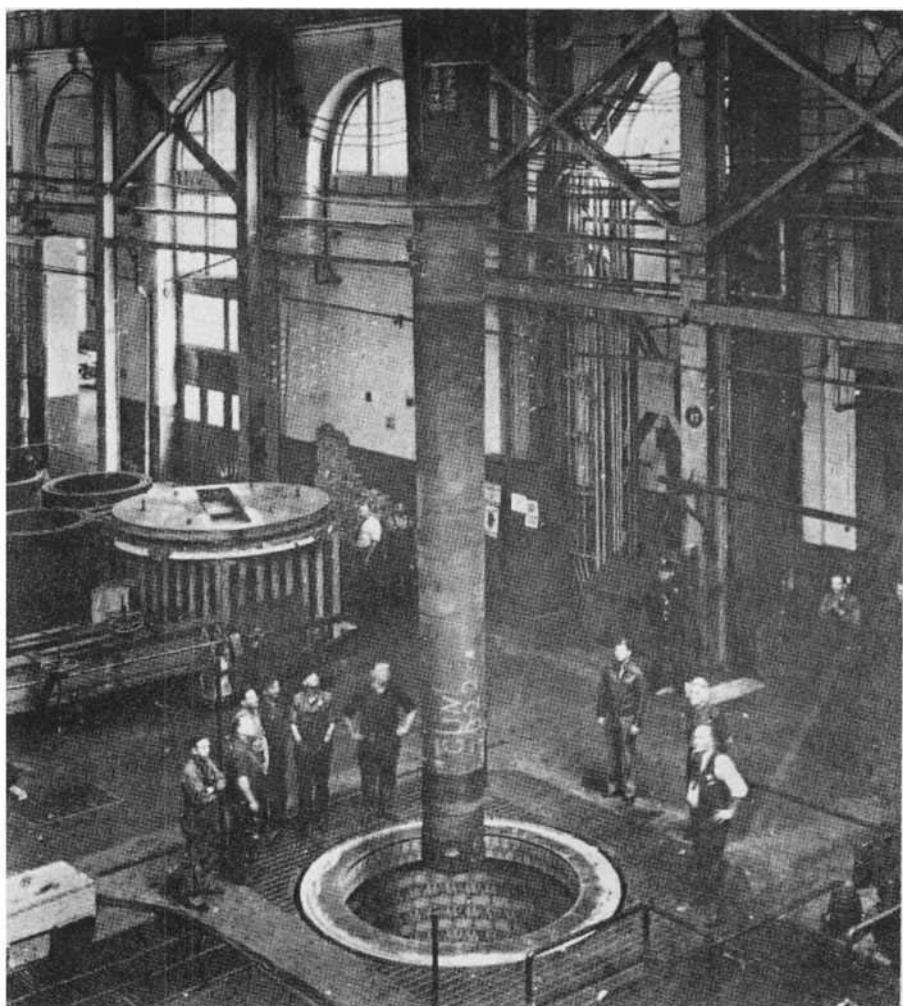
Fig. A-3 16-inch gun after shrinkage of B hoop in electrically heated pit at Watervliet Arsenal.

first applied to small arms barrels by firing a proof cartridge which produced a pressure of about 1.75 times the pressure of a service cartridge.

The distribution of the stresses in the walls of a cylinder, during the application of cold-working pressure, cannot be computed by the usual equations which apply only below the elastic limit. The stress distribution, however, can be closely approximated from special measurements showing the strains existing at various radii, and from the new elastic limit found in samples taken from various sections of the wall.

In applying this cold working process to cannon tubes the tube is placed in a container (Figure A-4), the interior of which has the shape and dimensions required for the gun after its bore is permanently enlarged by hydraulic pressure. A pressure of 44,000 to 100,000 psi is normally required to produce a 6% enlargement of the bore and a 40% increase of the proportional limit of the gun metal. The autofretted tube must be machined to finished dimensions. Removal of metal from the bore and from the exterior affects the residual stress condition, decreasing the benefits to some extent.

Additional considerations should be discussed which affect this cold-working process. During the war improved heat treating and better alloys gave physical characteristics far above those obtained from earlier alloy steels even after cold-working. As an example, a tensile strength of 150,000 psi was obtained on the 75-mm aircraft cannon without cold-working. This increase may be attributed directly to improvements of metallurgy. Manufacturing difficulties in cold-working also enter the problem. A cold-worked gun must be finished to a fine degree in order to be readily removable from the cold-work chamber. Cold-working is a severe test of metal, and the occurrence of soft spots after cold-working is rather frequent. Satisfactory equipment to build up the high pressure required and successfully transmit this pressure from the pumps to the bore of the tube is limited by the strength of the materials. The shortage of cold-working facilities detracts from the more obvious advantages of the process.
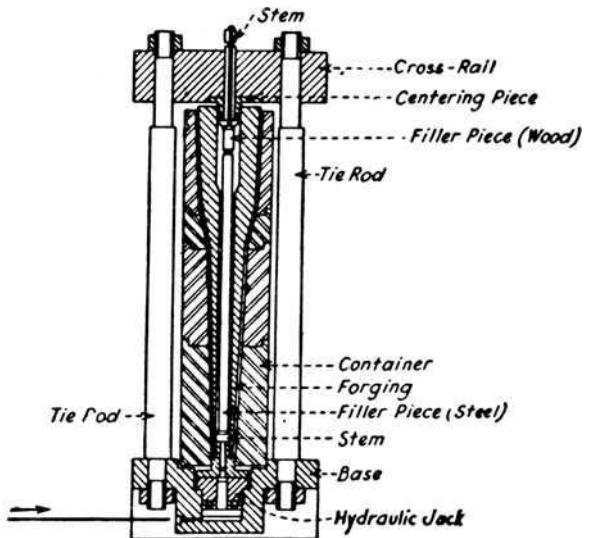
Fig. A-4 Partial layout of cold-working equipment.

A-4 BORING PROCESS

The finishing of guns involves various machining processes performed on the steel forgings, centrifugal castings, or seamless tubes. While the fundamental principles of ordinary machining are used, in these applications they represent especially engineered adaptations and techniques developed over a long period of time in various ordnance factories. Considering that it is not at all unusual for one of these gun tubes, which in the finished state may cost several thousand dollars, to be scrapped after finish-boring, definite techniques of manufacturing control must be adopted.

Naturally, all built up guns require more extensive machining operations, since before the assembly of two members the outer member is finished to include step boring (Figure A-5) and taper reaming of the interior, and the inner member to include finish-grinding of the exterior. The processes involved are similar for both small arms and cannon tubes except that for small arms the boring may be performed in a single pass of the tool.

Rough boring is done in an engine lathe, using a triangular or arrow shaped tool to open the bore, and a wood packed bit (Figure A-6) or series of such tools, to enlarge the bore. The tools cut from both ends of the tube toward the center in order to minimize errors caused by long tool travel. When the inner diameters of outer members are to be tapered from breech to muzzle to facilitate assembly, the operation consists first of cutting a series of cylindrical zones, progressively smaller in diameter. This step-boring is performed with packed bits. A series of tapered reamers, including roughing and finishing sets, is then used to blend the various zones into a continuous conical surface of the desired accuracy and finish.

Finish-boring is performed on the bore after the assembly of tube and jacket is complete or, in monobloc guns, after all exterior work has been performed. This operation is performed entirely from the breech end. The powder chamber is then bored to size and shape and finished by the use of special rough and finishing reamers which conform to the prescribed size and contour of the chamber.
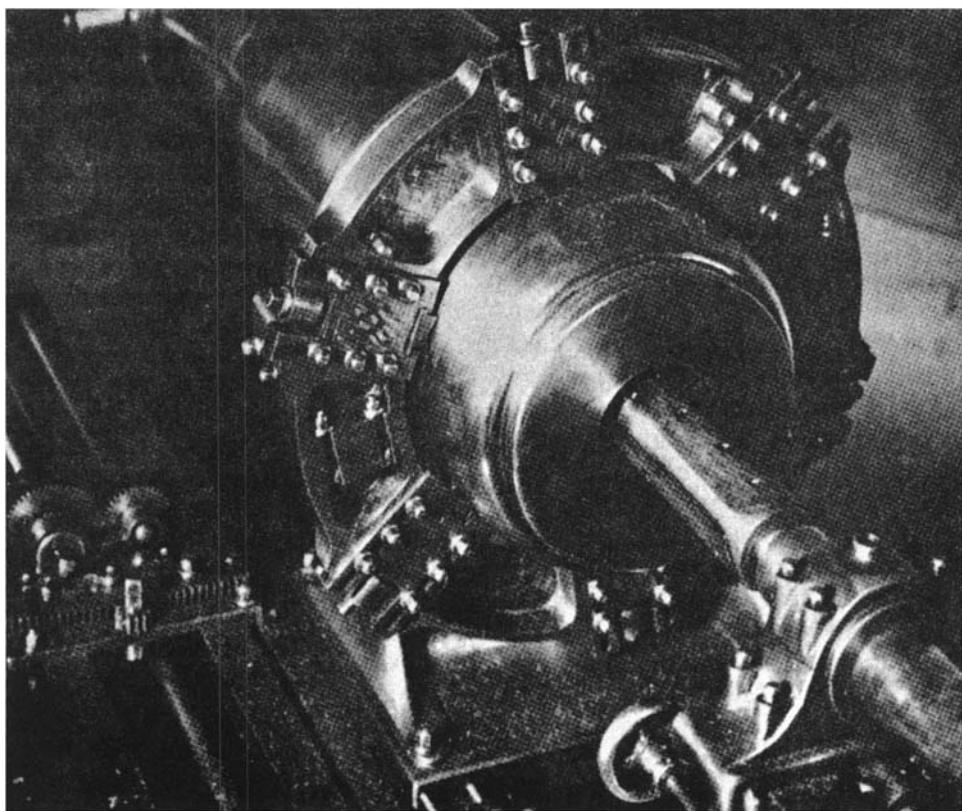
Fig. A-5 Model showing boring operation.
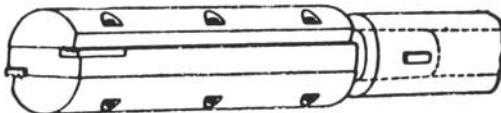
Fig. A-6 Packed bit.

A-5 HONING

The generation of gun bores from solid steel forgings or even hollow tubes is a slow and costly process. With a feed of 6 to 12 inches per hour for a finish-boring operation in a bore of 4.5 inches in diameter by 17 feet long, approximately 20 to 30 hours operating time per cut is required. The honing operation has contributed important alterations in the finish processing of gun tubes. Several installations have been made where it has been demonstrated that honing can follow at least a semifinish-boring operation, removing considerable stock in a small fraction of the time formerly required.

In one recent test, hydraulically actuated honing tools were used to hone a rough bored gun tube in 2.5 hours to an accuracy of 0.0005 in. The final surface finish was completed in 10 minutes with the removal of 0.0006 in. The older process of finish-lapping would have required several days. The latest type of equipment developed for honing large caliber guns is shown in Figure A-7.
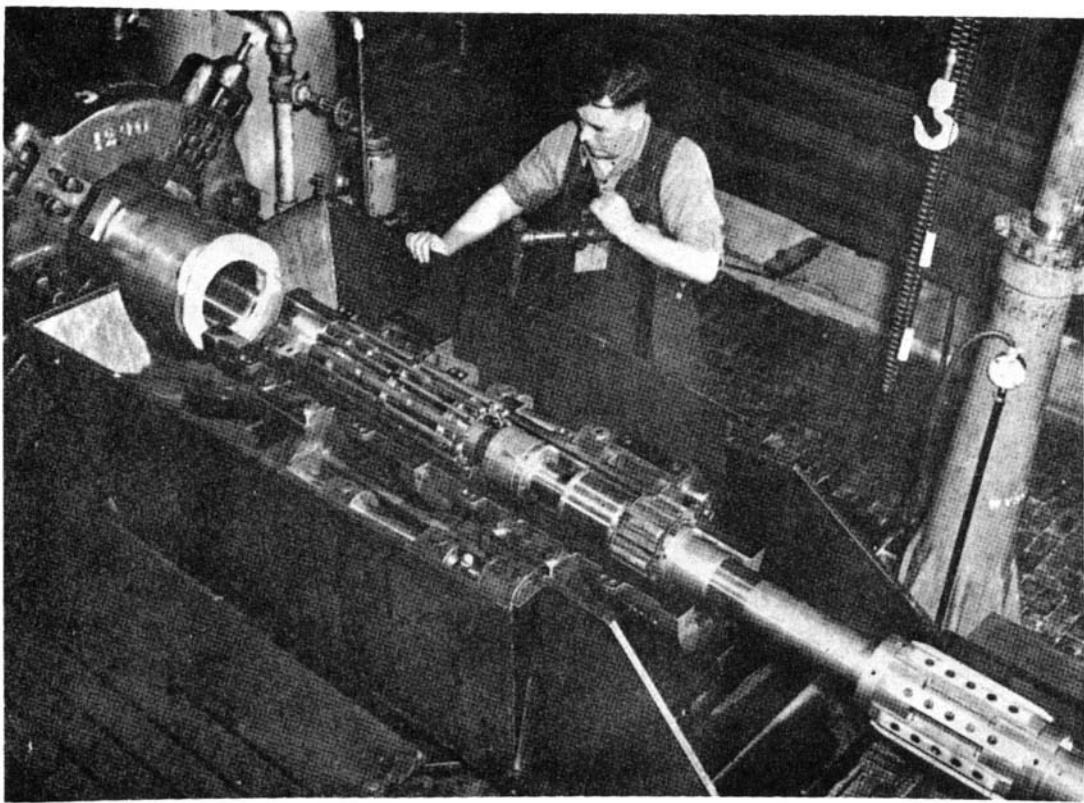
Fig. A-7 Large caliber gun hone.

A-6 RIFLING METHODS

For cutting rifling grooves two methods may be employed: The tool room or pilot lot method requires a special rifling machine similar to a gun lathe but without headstock or turning carriage (Figure A-8). The rifling bar is fed longitudinally by a motor at the tailstock end of the machine. Twist of the rifling is controlled by either an adjustable rail which conforms to the developed form of the rifling, or by a groove cut into the bar which contacts a key at the forward bar support. The rifling head at the end of the bar consists of a body with a shank for attachment to the machine and a sleeve which conforms closely to the finished bore of the gun. Guide grooves are provided in the forward end of the body for the support and accurate spacing of the cutters, any number of which can be used. A tapered plug inside the head holds the end of each cutter and provides the means for their radial adjustment outward for each cut When

one set of grooves is completely finished, the bar of the machine is rotated for succeeding grooves. Cutters must be able to cut the entire length of the bore without losing sharpness or varying the depth of cut. At least three cuts must be made to finish each rifling groove completely.

In order to eliminate the obvious disadvantages of rifling cutters, especially the great time involved, a new producton method has lately been employed, namely broaching. When used for the rifling of small arms, a gang broach (Figure A-9) is employed. This tool; with each individual cutter of slightly greater diameter than the preceding, is pulled through the gun tube and in two passes completes the rifling operation. The time and expense saved is considerable. Before the rifling broach was used, the cost of rifling a cal. .30 barrel was 17 cents. With the broach method the cost is 11 cents, including *the cost*
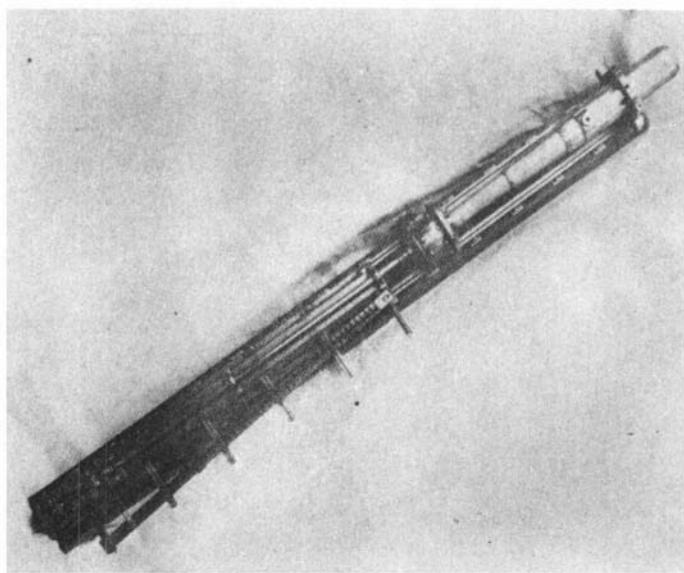
Fig. A-8 Model of rifling machine.
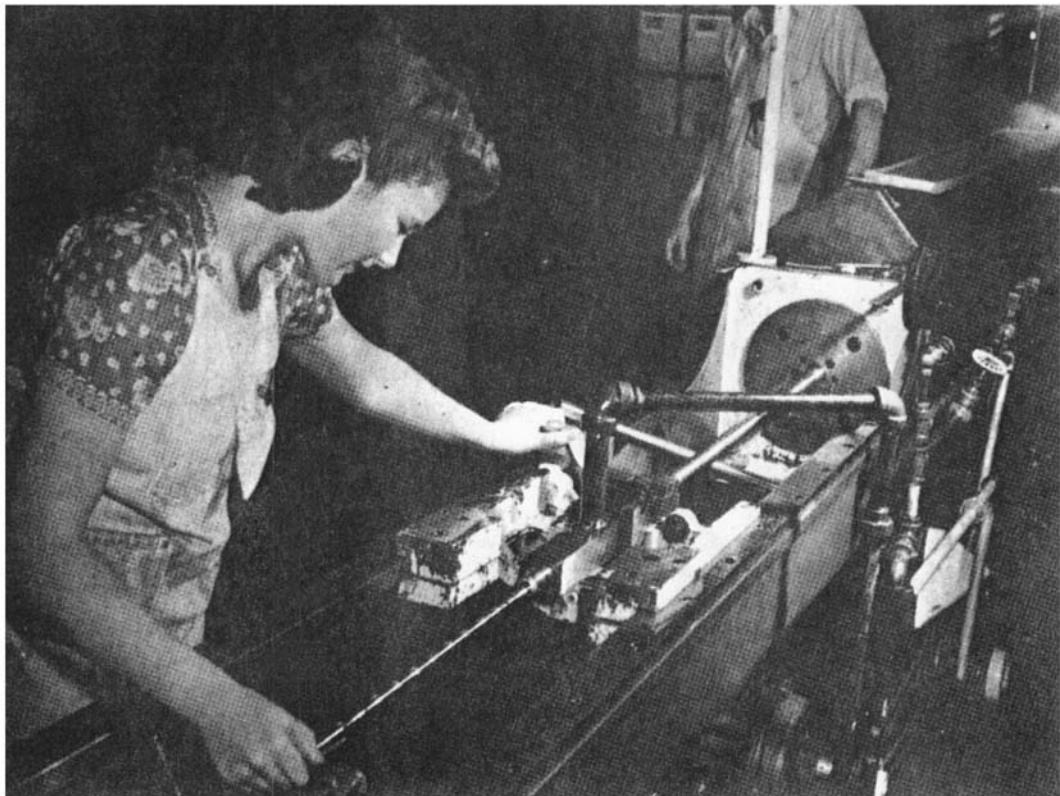
Fig. A-9 Small arms gang broach in use.
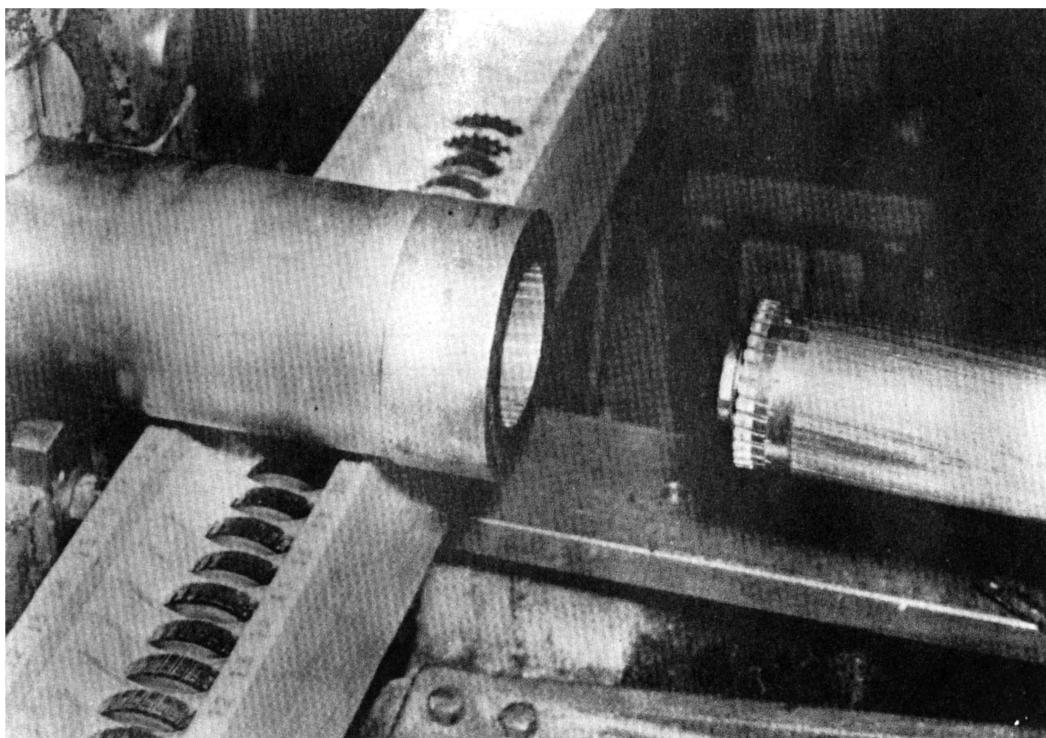
Fig. A-10   Series of rifling broaches.

of the broach. A rifling broach with tungsten carbide cutters for the rifling of stellite liners is currently under development.

Where broaching is employed in cannon tubes, large individual broaches must be employed (Figure A-10). Each such broach is of different size and must be changed after each pass of the tool. Successively larger broaches are used until the required groove depth is reached. Chatter is not entirely avoidable when broaching the rifling grooves in medium caliber tubes. Usually such imperfections are not more than 0.0005 inches deep and are not of sufficient importance to cause rejection; however, in order to provide the highest quality in fighting materiel, honing of the rifling grooves is employed. For rifling with increasing twist a special honing tool must be used in which the stone carriers are free to rotate, allowing the stones to pivot with the change in helix angle.

A brief description of a recent radical method of small arms rifling is in order at this point. In the case of the Carbine, Cal. .30, M1, the button method of rifling has been used with remarkable success. It consists primarily of cold swaging the grooves into the specially prepared bore of a barrel blank. This is done by forcing the button of very high grade tool steel (Figure A-11) through the bore by means of a hydraulic ram. The barrel blank is drilled and reamed to a predetermined diameter which is sufficiently below the desired bore diameter to allow for a resulting increase in diameter due to expansion which takes place during the swaging operation. The wall thickness is very important since a thin wall will allow the button to expand the blank too readily and an insufficient groove depth will result. To decrease the friction between the button and the bore, copper plating is applied to the bore for lubrication. No metal is removed as the button is passed through the bore; metal is merely displaced, resulting in an increase of the outside diameter. The twist of the rifling is achieved by the groove element of the button which automatically causes the button to rotate

LAND IRONING BUTTON

GROOVE AND LEAD BUTTON

GUIDE

RIFLING BUTTON

← A ← B

← A ← B

SECTION AA
GROOVE AND LEAD BUTTON

SECTION BB
LAND IRONING BUTTON
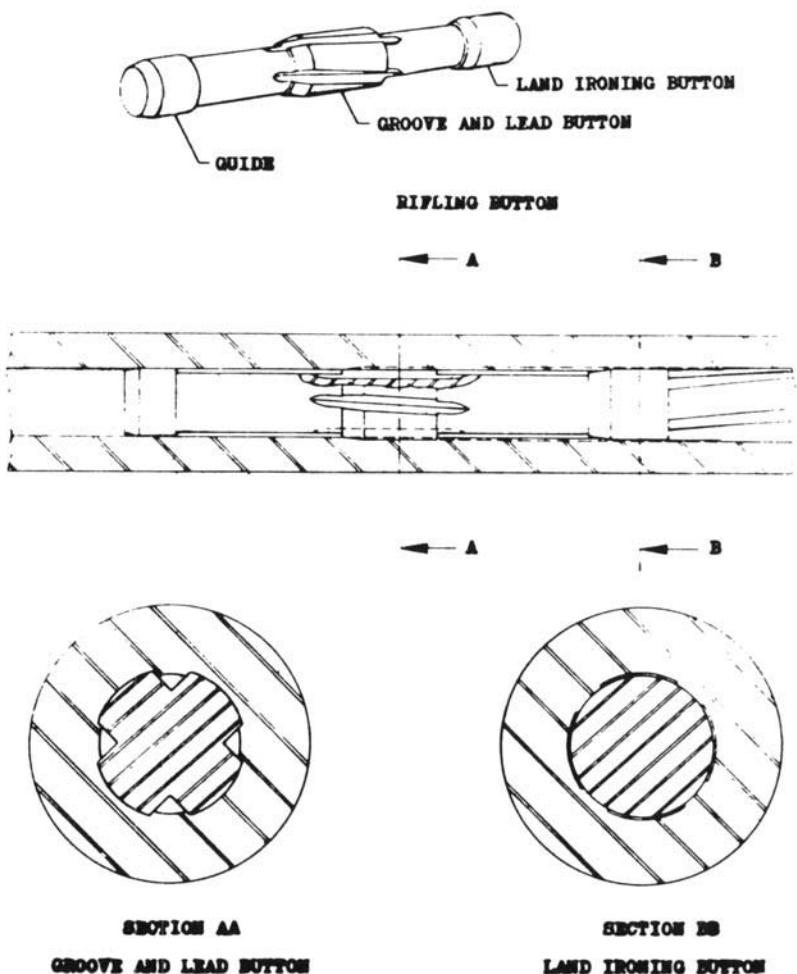
Fig. A-11 Rifling button.

the proper amount. The slightly raised edges along the corners of each land are ironed smooth again by the third element of the button. Such cold-working causes a slight increase in the hardness and should improve the wear resistance characteristics of the barrel. Only one pass of the machine is required to produce the finished rifling.

A-7 TAPERED-BORE GUNS

The various considerations of gun construction which have already been discussed in this chapter present a somewhat different problem when applied to guns employing the tapered-bore principle. A good example of a tapered-bore (or Gerlich principle) gun is the German 28/20 Pak antitank gun whose bore tapers from 28 mm at the breech end to 20 mm at the muzzle. The tapering of the bore is not uniform. Beginning at the origin of the rifling, at the breech end the bore is cylindrical for the first 18 inches. The next 9 inches of the barrel has a rapid taper of

.022 in./1 in. The taper of the last 23 inches of the tube decreases to .002 in./1 in. The pitch of the rifling is not uniform. During its travel through the bore the projectile is swaged into a smaller diameter, improving obturation of the powder gases but increasing the energy needed to squeeze the bullet through the tapered bore. The projectile referred to achieved a muzzle velocity of 4600 ft/sec, but loses about 40% of its kinetic energy in 300 yards, whereas the American 20-mm AP-T shot M95, with a muzzle velocity of 2800 ft/sec, loses only 28% of its energy in 300 yards.

From the viewpoint of a gun manufacturer, such a gun presents special problems. The tapered boring and reaming of the tube is very complicated: The rifling of the tube is also difficult and costly in time and expense involved.

A-8 EROSION PROBLEMS

As the demand for lighter, yet longer range or higher velocity weapons increases it should be apparent that the problem of gun tube erosion must receive increased attention. Cooperation from troops must be obtained, in such ways as limiting the rate of fire to the minimum required to accomplish the tactical mission in order to eliminate overheating of the tube. The gun manufacturer however, must continually strive for long tube life under the most adverse conditions.

One of the earlier, rather negative attempts to prolong gun life was the use of a removable loose liner. This was an inner cylinder containing a complete rifled bore, which was inserted into and locked inside the tube. The tube could be reconditioned by replacing the worn liner with a new one. This method tended to expedite the field repair of worn guns, but the added expense of extra machining operations on both the liner and the gun tube was too high when compared with improved monobloc construction. Large built up guns over 6-inch caliber can be relined by shrinkage methods. This is an arsenal job.

A fixed stellite liner (Figure A-12) for the cal. .50, M3, machine gun has recently been standardized. Liners of nickel alloys are under consideration but are not as yet satisfactory. The added gun life achieved with the use of the stellite liner in the cal. .50 machine gun results in
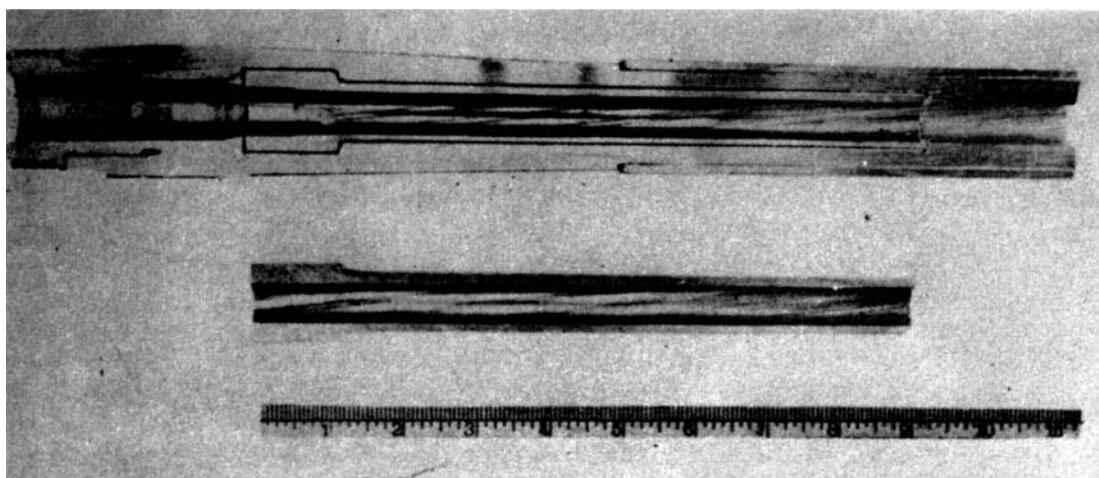
Fig. A-12 Cutaway view of caliber .50 machine gun barrel, showing stellite liner.

a unit cost increase from $9.00 for the old barrel to about $26.00 for the new one; however, the barrel life under continuous fire increases from 200 rounds to 4000 rounds.

Another method, originally used by the Navy and now used by the Army in its 90-mm high velocity tank gun, is chromium plating the gun tube. The thickness of the plating is approximately .005 inches. Chrome plating of the chambers of 57-mm and 75-mm recoilless rifles to a depth of .01 inch is also being tried

One other method of improving erosion resistance warrants a brief description: Induction heating of the lands and grooves above the critical temperature, followed by either water or air quenching, has raised the Rockwell C hardness of the surface from 30 to 50. Such treatment however shrinks the bore diameter slightly (.001 inch in 75-mm gun). Studies on this are continuing.

INDEX